Electronic Depiction of Instrument Approach Procedure (IAP) Charts

Phase I: Development and Preliminary Evaluation

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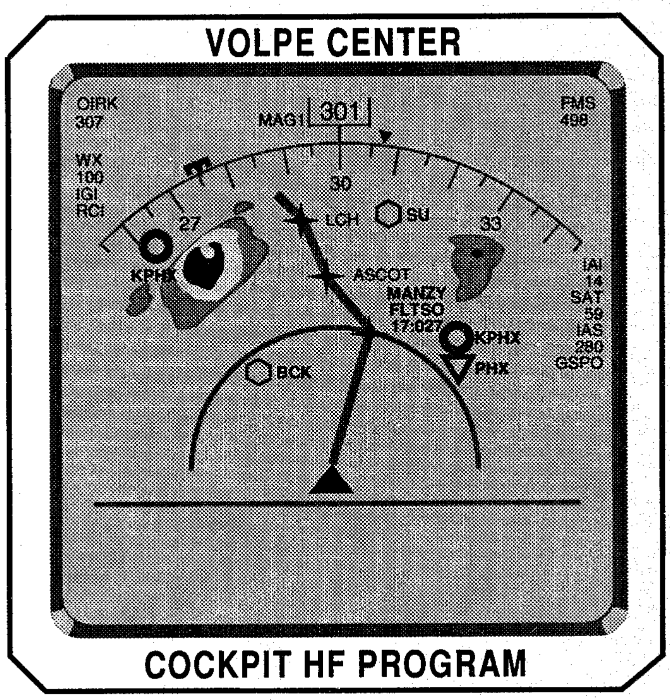

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13. ABSTRACT (Maximum 200 words)

This report describes the research program being conducted at the Volpe National Transportation Systems Center on the development of electronic aeronautical charts. The design of electronic aeronautical navigation charts raises many interrelated human factors issues including those pertaining to the physical aspects of the display screens (e.g., location in the cockpit, screen resolution, color capability, brightness range) and those affecting the pilot interaction with the software (i.e., pilot interpretation of the information presented). A limited amount of research has been conducted on the design of electronic chart systems for instrument approach procedure (IAP) charts. The results have indicated that not all of the information printed currently on paper IAP charts is needed to fly instrument approaches. Current issues in electronic chart design are discussed in this report. Results from a study that compared three alternative design formats are also provided. Based on the findings from this study, it was determined that electronic charts are a benefit to pilot situation awareness. Newer design formats that use small amounts of display space are also presented.

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Instrument Approach Procedure (IAP), electronic chart display, aeronautical navigation chart, mental workload, information requirements

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PREFACE

This document is a preliminary report on the development of a research program conducted at the Volpe National Transportation Systems Center (VNTSC) designed to investigate the electronic depiction of aeronautical navigation charts. An electronic charting display laboratory, the Cockpit Human Factors Laboratory, was created at VNTSC to provide researchers with the tools required to carry out the research.

The authors wish to express their appreciation to Mr. Frank Sheelen, of the W.T. Chen Company, for his efforts in the development of the software used for the creation and presentation of electronic aeronautical charts and touch-screen user interface.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m_2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yeards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0		1		2		3		4			5		6			7			8		9				10
CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

TABLE OF CONTENTS

LIST OF TABLES/FIGURES

EXECUTIVE SUMMARY

This document is a preliminary report on the development of a research program being conducted at the Volpe National Transportation Systems Center (VNTSC) designed to investigate the electronic depiction of aeronautical navigation charts. The report is divided into four sections. The first presents an overview of the issues in electronic charting that will be addressed in subsequent research reports. The second part describes the research tools that have been created at VNTSC and provides further discussion of the areas of research that are being explored. The third section provides results from a pilot study that explored simulator flight performance using three prototype electronic chart designs. The final section presents specific design concepts under development for future research.

The design of electronic chart display systems raises many human factors-related issues. Considered broadly, these can be broken into issues about physical aspects of the display screens (e.g., location in the cockpit, screen resolution, color capability, brightness range) and issues about the pilot interaction with the software (i.e., pilot interpretation of the information presented). These issues also interact with each other. For example, display area size has an impact on what information can be presented. At the moment, there are still more questions than answers. A limited amount of research has been conducted on the design of electronic chart systems for instrument approach procedure (IAP) charts. This research has focused primarily on professional flight crews; therefore, the results may not be completely generalizable to the general aviation (GA) population.

The results have indicated that not all of the information printed currently on paper IAP charts is needed to fly instrument approaches. Further, pilots have had faster information retrieval times using electronically displayed IAP charts than paper charts and stronger preferences for the former. How small a chart display can be and still be useful remains an issue to be resolved. Additionally, what information is necessary to fly safely, what is it needed for, and when is it needed? Answers to these questions await further study.

An electronic charting display laboratory has been created at VNTSC that provides researchers with the tools required to investigate the issues raised above. A flight simulator has been equipped with an LCD display panel for developing and testing prototype chart displays. Although the display screen is located in a fixed position in the simulator, the laboratory setup provides complete control over other aspects of the chart design. Future studies will be able to address issues of the impact of the physical aspects of the display environment on pilot performance, as well as the impact of software design on pilot interpretation of electronically presented aeronautical charts. Plans are under way to equip a Piper Aztec with a comparable display screen so that critical design issues can be tested in the air.

A preliminary investigation using the electronic charting laboratory at VNTSC has been conducted. Three different electronic displays of IAP (IAP) charts were tested in the flight simulator. The first display format emulated existing paper charts. The second added

dynamic information (i.e., animated graphics and text) of the ownship position to the first format. The third contained only tabular information of waypoint names, distance, headings, and altitudes. Pilots flew two approaches with each electronic display and two with paper IAP charts. Performance and subjective measures were collected. No significant differences were found on performance measures for the different display conditions. Strong subjective preferences were found for the second display format. These data indicate that pilot performance is not significantly diminished by providing IAP information in an electronic format. However, performance is not enhanced either. The addition of the dynamic information to the electronic chart was reported by pilots as increasing situation awareness in comparison with the other display formats. This finding, in conjunction with the result that pilots had no difficulty flying approaches with only tabular data and no maps, suggests that electronic map displays benefit pilots the most by providing information that improves situation awareness. Pilots also reported that the tabular display removed any ambiguity about the IAP and made it relatively easier to fly.

The final section of this report presents some of the display design concepts that are currently being developed in the electronic charting laboratory. The success of the tabular display in the preliminary investigation has led to an improved design in which information no longer needed for the flight is removed from the display. A hybrid display is also in development that incorporates a plan-view map with a tabular display. This design capitalizes on the reduced ambiguity of the text-based instructions and the heightened situation awareness of a dynamic map. The size of the map is also adjustable so that the issue of size on utilizing dynamic map displays may be investigated as well. It is possible that a small map display may still provide enhancements to situation awareness, but may reduce a pilot's tendency to rely on the map for course guidance (i.e., flying the map). A third design concept presents a radically different combination of text and map displays. In an effort to compress IAP information into a small space, waypoints are presented along a straight vertical course line, with turns and altitudes indicated along side of the waypoints in text form. Position along the course is provided by a moving cursor. The vertical course line is expected to provide reasonable tracking information to the pilot, and the removal of turns from the course display reduces the size of the screen that is needed. However, situation awareness is not enhanced with this chart design as in a conventional plan view. All three formats will be evaluated in the future.

1. INTRODUCTION

The program of research described in this report has been designed to explore the human factors issues associated with the electronic depiction of an instrument approach procedures (IAPs). Advancements in electronic, flat-panel display technology have made possible the incorporation of electronic display devices into most cockpits, both commercial and general aviation (GA). It is anticipated that these displays will eventually depict aeronautical charts, including IAP charts. Two of the largest incentives for this development are the cost savings of eliminating paper charts and the ease of updating electronically stored information as compared with information printed on paper. The transfer of information from a paper chart to an electronic display is not a straightforward procedure, however, and many factors affecting the human operator's use of the new technology must be considered for effective development of an electronically depicted aeronautical chart.

The first section of this report describes some of the issues that need to be considered in the development of electronic displays of aeronautical chart information. The second section details the electronic charting display tools created at the Volpe National Transportation Systems Center (VNTSC) Cockpit Human Factors Laboratory and discusses the intended research objective of specific features. The third section presents data from a preliminary study, gathered during IAPs flown in the VNTSC flight simulator, using three different electronic chart display designs. The third section provides a description of three new electronic chart design concepts. The final section explains future directions of research and development in electronic chart design.

1.1 ISSUES IN THE DESIGN OF ELECTRONICALLY DISPLAYED AERONAUTICAL CHARTS

This section provides an overview of some of the human factors issues in the design of electronic charting systems. Rather than providing an exhaustive list, key issues were raised and questions for further study noted. The issues addressed are:

1. Location of the display in the cockpit

2. Size of the display

3. Physical characteristics of the display device (e.g., resolution, brightness, and contrast)

4. Formatting of information.

A brief review of some of the current research on electronic charting is also presented.

1.1.1 Location in the Cockpit

The location of the display in the cockpit is an important issue in the design of electronic displays of aeronautical charts. Paper charts are typically held in front of the pilot in a clip on the yoke, in the pilot's hand, or on the lap. The pilot is free to move the chart to any desired location in order to maximize the lighting conditions for viewing the chart. An electronic display most likely will be mounted in a fixed position in the cockpit. Pilots will have to change their scan patterns to incorporate the information on the electronic display. Additionally, the ambient lighting may not always be optimal for viewing this display device and some conditions may make the display impossible to read (e.g., when the display is under direct sunlight). Display technologies differ with respect to viewing angle, brightness, contrast, and sunlight reflection. The location of the display device in the cockpit, therefore, will be a critical consideration for the installation of any electronic charting display and will vary with the type of the display. The parameters that define the envelope of safe locations for cockpit installation will have to be determined for each display technology.

The fixed distance of electronic display screens from the pilot in the cockpit imposes minimum size requirements for text and symbols. Currently, the pilot is free to move paper charts as close as needed for viewing small symbols and text. However, the range of text sizes and symbols on paper charts does not allow for quick interpretation at distances greater than arm's length. Therefore, a minimum size must be established for text and symbols on electronic displays which will be even farther away in the cockpit than paper charts. This issue will also have an impact on chart design.

1.1.2 Display Size

Current paper charts come in a variety of sizes, with the smallest being single-sheet IAP charts, and the largest being fold-out enroute charts. Cockpit electronic displays will be of fixed size and, due to the limited amount of space available on most cockpit instrument panels, will likely be smaller than even the current IAP charts. The transfer of information from paper charts of varied size to an electronic display of fixed size poses several questions to the electronic chart designer including, for example:

- How much of the current information on paper charts needs to be transferred to the electronic screen?
- How much of a given chart needs to be seen at one time?
- How quickly does a pilot need to be able to see new information?

The minimum portion of information that is needed by the pilot for electronic depiction of aeronautical charts, from the set of information that is presently shown on paper aeronautical charts, will have to be determined. Given the considerations of display size stated above, alternative chart designs will have to be developed and evaluated on electronic display

devices of different sizes and in different cockpit installations.

1.1.3 Display Screen Characteristics

Electronic display screens have inherent physical characteristics that are different than paper charts. Some impose a limitation on the display of information in the cockpit. For example, resolution, or the ability to display small details, is lower on electronic display screens than on paper charts. Inch-for-inch, paper charts are able to display more information than electronic display screens. A simplification of the spatial information on current paper charts will be required for electronic presentation. Text fonts will have to be simplified, and as noted above, will have to be increased in size. Some of the current highlighting techniques, such as boldface and underlining, may have to be eliminated if they do not show-up well in an electronic format. Text will have to be displayed horizontally. This will dramatically change the appearance of charts and will likely require some new design practices.

Other electronic display characteristics create new possibilities in aeronautical chart design. Many electronic display screens have the ability to display information in different colors and to change the color scheme and contrast ratios dynamically. Although current paper charts utilize color-coded information, they are limited to what is printed on the page. The colors of specific items on the screen can be changed on electronic displays reflecting the phase of flight and highlighting critical information that changes during the flight. This aspect of electronic display screens may offset the information loss due to the lower resolution. Pilots also prefer color-coded displays to monochromatic formats (Mykityshyn, Kuchar, & Hansman, 1994). The choice of an optimal color coding scheme remains an open question (e.g., Smallman & Boynton, 1990) and there are several candidate suggestions (e.g., SAE, FAA AC 25-11, Boeing EFIS). Additionally, color coding does not always provide performance advantages, and since not all display devices will have color, alternatives to color-coding will have to be considered.

Electronic map displays also offer the possibility of dynamic features. These include pages with varying information that can be changed manually or automatically (e.g., a selection of charts), as well as moving airplane symbols representing the pilot's current position on a map, or a moving map that continually changes to reflect the pilot's current position (i.e., track-up). Also, moving airplane symbols and track-up displays are not limited to single, lateral depictions of the airspace. Vertical position can also be indicated.

Dynamic features allow for the possibility of incorporating more information in a limited space than in a static display. Moving aircraft symbols and track-up displays offer the possibility of increased situational awareness and improved tracking performance. However, these features also may add to confusion and disorientation if the display is not predictable and if pages of information are not easy to manipulate and logically structured. Additionally, accuracy of information depends on the physical characteristics of the display. Dynamic electronic chart displays have to be evaluated within the context of the physical limitations of

the display screens to determine the relationship between changing information, screen size, resolution, and the ease of use of the display.

1.1.4 Formatting of Information & Pilot Interpretation

Some dynamic formats possible with electronic displays create the potential for misinterpretation by the pilot. For example, electronic charts may have a zooming feature that allows the pilot a close-up view of a particular section of a chart. But, in the close-up view, terrain features separate, creating the false impression that they are farther apart than they really are. Limitations in the database from which information is drawn and limitations in the resolution of the display determine the positional accuracy of the chart information. Some method of informing pilots of the scale accuracy of the display will have to be determined.

The incorporation of a moving airplane symbol or track-up map displays adds an additional utility to aeronautical charts. The electronic displays can now be used for both navigation and manual control of the aircraft in three dimensions. Evaluation of electronic displays of aeronautical charts will also have to consider the impact of the chart on the pilot's tracking performance. It is possible that electronic displays may become quite compelling and the pilot may inadvertently "fly the map." That is, the information presented for lateral and vertical guidance may appear to be sufficient for a pilot to completely control the aircraft by referencing only the map display. This possibility requires the design of displays with suitable resolution to make this method safe or the creation of designs that discourages the pilot from excessive use of the display.

Display screens sometimes provide a potential tradeoff between situation awareness and tracking performance. Adequate tracking on a low resolution display requires a magnified view of a chart. This necessarily reduces the global picture available to the pilot which potentially reduces situation awareness. Electronic chart formats will have to be evaluated on this dimension, and optimal magnification levels for tracking and situation awareness will have to be determined. This issue will be further complicated by the consideration of different display sizes and limiting physical characteristics.

The choice of interface to the display device for selection of information and the configuration of the information on the display will also have to be considered in the design of electronically depicted charts. Clay (1994) has attempted to catalog many relevant design principles and guidelines for the creation of electronic chart displays. Although human factors guidelines exist for display design and interface design, many of them do not apply in the unique, time critical environment of the cockpit. During an approach, pilots have little time to interact with additional equipment and, therefore, the display interface must be easy to use. Different interfaces will have to be explored to find optimal solutions. Automation may reduce the number of physical interactions with the display device required by a pilot, but the sequence of information to be presented will have to be developed through careful study. The configuration of the information must also be easy to interpret. There are many possible

configurations of information. Criteria must be developed to guide designers in the creation of displays that pilots can interpret quickly.

1.2 RECENT RESEARCH ON THE ELECTRONIC DEPICTION OF AERONAUTICAL CHARTS

1.2.1 Information Requirements

Interest is growing in determining the information requirements of pilots using aeronautical charts in order to optimize electronic chart formats. The phase of flight requiring the greatest amount of information access, the IAP, has received the most attention. Hofer et. al. (1992) and Ricks et al. (1994) attempted to determine the information required of pilots during an IAP and to categorize that information meaningfully. Zirkler and Morton (1990) developed an engineering model to determine the information requirements of paper IAP charts and a hypermedia-based display. Clay (1993) determined the cognitive components of flying IAPs. These studies concluded that the information needs of the pilot during an instrument approach change with the phase of flight and vary from pilot to pilot. It is not likely, therefore, that an automated system will be optimized for all pilots, or that every pilot will need all of the enhancements to aeronautical charts that electronic depiction will provide.

1.2.2 Empirical Studies

Mykityshyn, Kuchar, and Hansman (1994) measured information retrieval from several electronic display formats and from conventional IAP paper charts. The electronic formats offered pilots a "decluttering" mechanism that reduced the amount of information presented to them from the content on the paper charts. Based on their own preferences, pilots were able to configure the decluttering mechanism. Faster response times were obtained to probe questions for a color-coded, decluttered moving map display than for conventional paper charts. Pilots did not perform better with a monochrome electronic displays than with paper charts. These authors also reported strong pilot preference for color coding of information and for a north-up orientation of the plan view map.

Hofer et al. (1992) and Hofer (1993) found similar results to the study above. Faster information retrieval times were obtained for decluttered electronic IAP displays than for paper charts. Pilots preferred the north-up orientation electronic display with a moving airplane symbol on both plan and profile views to a track-up electronic display and conventional paper charts.

In all three of these empirical studies, decluttered electronic display designs were preferred by pilots. These results indicated that all of the information contained on current paper IAP charts was not always needed to fly instrument approaches. The cleaner appearance of decluttered electronic charts compared to paper charts is a clear advantage for electronic displays. However, what information may be eliminated safely from a chart at the pilot's

choice and what information can be removed based on the phase of flight must still be determined.

The studies cited above utilized conventional paper chart designs in their electronic displays, incorporating two-dimensional plan view and profile view maps. However, other designs are possible. Haskell and Wickens (1993) and Wickens, Liang, Prevett, and Olmos (1994) have designed and tested systems that provide a display of information in three dimensions. Results from these studies indicate that information presented in three dimensions on electronic displays can be used effectively by pilots for flying instrument approaches. These studies represent just a few of the many possibilities for the electronic depiction of aeronautical chart information. It is worth noting, however, that all of the empirical studies presented so far have used relatively large display devices and sophisticated computing equipment for the generation of their displays. Additional research is needed to determine the possibilities of small displays and low-cost computing equipment that is likely to be installed into smaller aircraft.

The utility of electronic displays for maintaining situation awareness also has been addressed empirically. Endsley (1993) found that pilots rated aircraft position information as very important for maintaining situation awareness. Several studies have shown that pilots prefer north-up maps with moving airplane symbols depicting ownship position to track-up maps for maintaining situation awareness (Mykityshyn, Kuchar, and Hansman, 1994; Hofer, 1994; Marshak, Kuperman, Ramsey, and Wilson, 1987). North-up maps, however, are not necessarily better for maintaining situation awareness (Aretz, 1991; Hofer, 1993; Wickens, Liang, Prevett, and Olmos, 1994) and, in some situations, have been found to be inferior to track-up displays (Marshak, Kuperman, Ramsey, and Wilson, 1987). These studies employed a probe question technique for measuring situation awareness. Although this technique has been shown to have relatively little impact on flight performance (Endsley, 1993), alternative methods for measuring situation awareness need to be developed that interfere less with normal flight operations.

Track-up displays have generally been found to be superior to north-up displays when used for course guidance (e.g., Haskell and Wickens, 1993; Wickens, Liang, Prevett, and Olmos,1994). Since electronic displays of IAP charts can be easily configured in north-up and track-up formats, the displays themselves can be integrated into other cockpit equipment used for course guidance or traffic avoidance. Initial attempts at incorporating electronic chart displays into other flight deck systems have received mixed reviews from pilots (Mykityshyn, Kuchar, & Hansman, 1994; Hofer, 1993). More work is needed on the issue of integration with other displays.

2. VNTSC ELECTRONIC CHARTING SYSTEM

The Cockpit Human Factors Laboratory at the VNTSC has developed a set of tools for creating prototype electronic aeronautical chart displays. The tools consist of a display screen in a Frasca 242 flight simulator and a collection of software programs that display different electronic chart designs on the screen. The system is a fully functional part of the simulator environment, allowing for simulation flight assessment of alternative design formats. Plans also are under way to create a stand-alone device that can be used in an airplane as well. This section describes the tools that have been created and the research requirements for which they have been designed.

2.1 HARDWARE

The heart of the display system is an 80486 processor PC that is linked to the Frasca simulator over a local area network. The PC is external to the simulator and a cable connects the monitor port of the computer to the display screen inside the simulator. The display screen is a color, VGA (640x480 pixels), active matrix liquid crystal display (AMLCD), measuring 8" horizontally by 6" vertically. These dimensions yield a screen resolution of about 80 dots per inch (dpi). An acoustic-wave, touch-sensitive screen covers the AMLCD and is connected to the PC over the serial port. Adjacent to the display area are 10 push-button switches that are linked to the PC through the keyboard. A schematic representation of the display in the instrument panel is provided in Figure 1.

This hardware configuration has evolved over the past two years and offers many advantages and a great deal of flexibility. The PC is a readily available commercial product, the power of which is currently available in lap-top computers and easily incorporated into most cockpits. The LCD is larger than the displays that some manufacturers are likely to use, but this allows for a great deal of flexibility in reconfiguring the displays. Display area issues are easily dealt with by using smaller portions of the screen. The display has a relatively low resolution, so the limitations of resolution of display design are readily determined. The color capabilities of the display allow for testing of color, grayscale, and pattern coding of information. The touch sensitive screen provides flexibility in designing the user and experimenter interfaces to the system. The touch screen sends a signal to the PC indicating where the user is touching the screen. This signal is interpreted the same as a mouse peripheral device. The acoustic wave screen is also pressure-level sensitive. It is possible, therefore, to test the viability of a touch screen interface, requiring specific pressure levels to activate the display options. This may prove useful in an airplane, when turbulence may cause unintended contacts with the display screen. Sensitivity on the screen can be adjusted so that only deliberate touches are registered. The buttons adjacent to the screen also provide a reconfigurable interface to the system.

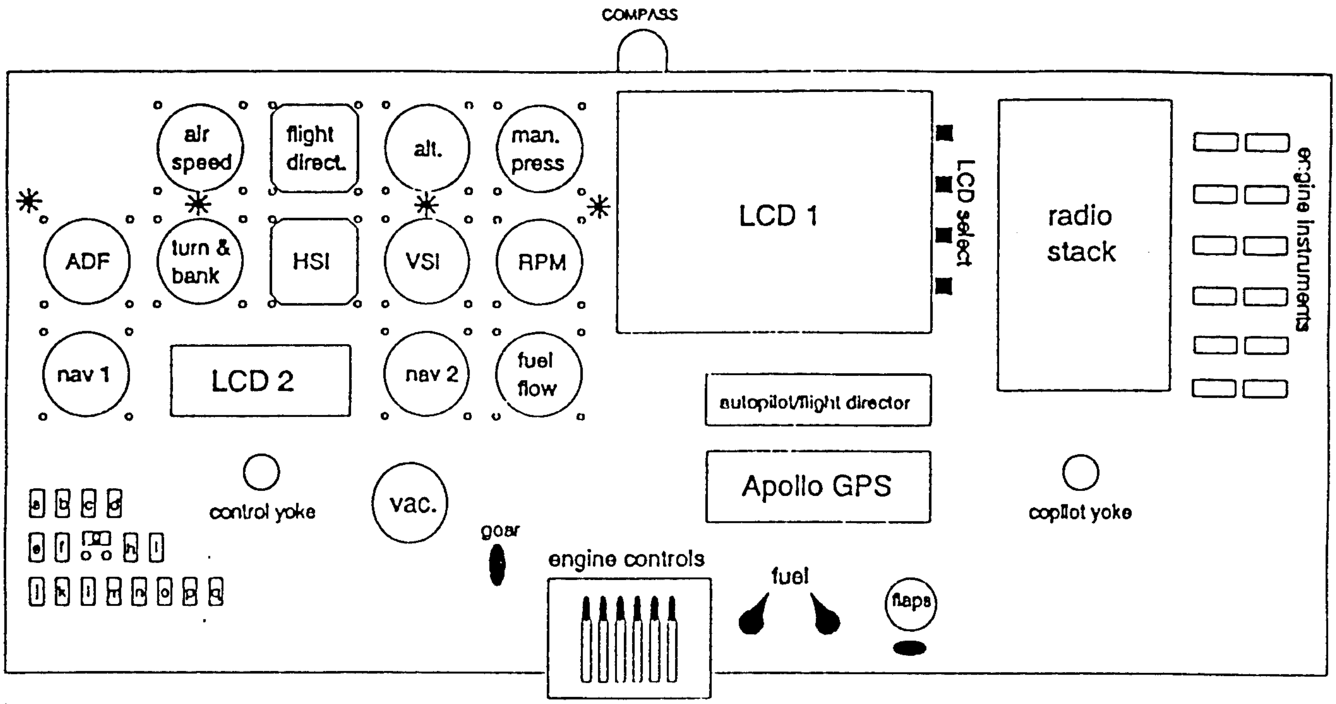


Figure 1. A schematic illustration of the Frasca Instrument Panel. The area marked LCD1 is the electronic display screen used for displaying electronic charting information.

2.2 VIEWING ENVIRONMENT

An overhead fluorescent light in the cockpit provides general lighting. The AMLCD is backlit and the intensity of the display is adjustable in the cockpit. The display screen is mounted in a fixed position on the instrument panel. The distance of the viewer from the screen varies with the position of the seat, but, usually, it is approximately 32 inches from the eye position to the center of the screen. The screen is located to the right of the viewer, approximately 32 degrees to the center. The location of the display imposes restrictions on the design of displays, however, these are the same real constraints as are faced in an airplane. Future developments will allow for a moveable display screen.

2.3 SOFTWARE & SYSTEM REQUIREMENTS

All of the software used for display development and presentation is written in Microsoft Visual Basic, running under Windows NT. The display host PC shares information over the local area network. Information about the simulated airplane position, heading altitude, and vertical speed are taken from other PC systems on the network.

2.4 DISPLAY SCREEN CONFIGURATION

The display screen can be arranged in any configuration desired. Currently, design prototypes have utilized two dimensional maps, such as the plan and profile views on IAP charts. The size of the maps is variable, and the scale displayed within the maps is also adjustable. Sections of the display can be dedicated to text displays, graphic displays, or a combination. Touch-sensitive buttons also have been presented as a user interface. Dynamic information can be displayed anywhere on the screen. The flexibility available in screen configuration allows for testing multiple display formats.

The relative advantages of map displays over tabular information display is an issue currently under examination. Future plans include consideration of map size on navigation performance. Figure 2 presents an illustration of one of the prototype electronic charts that have been created.

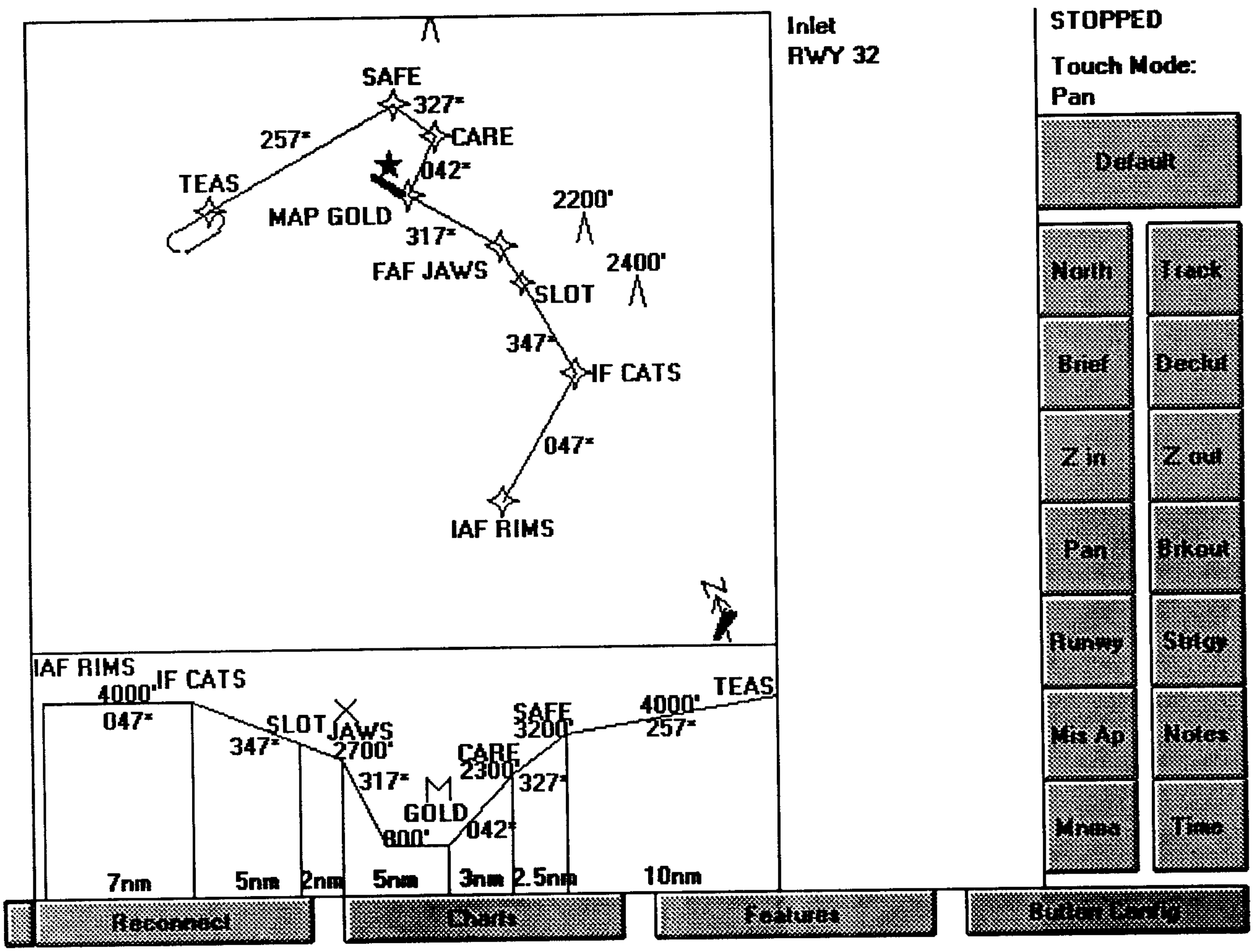


Figure 2. An illustration of a display design using the electronic charting tools at VNTSC. Plan and profile view maps provide static and dynamic information. Text information is presented in the center column. The right area of the screen is dedicated to touch-sensitive interface.

Plan and profile view maps occupy the left side of the screen. A center strip provides a dedicated area for text presentation. The right portion of the screen is dedicated to the user interface.

2.5 DISPLAY APPEARANCE

The color capabilities of the screen allow for setting the color of every item in the display. Any color combination is possible, including black-on-white and white-on-black. Gray scale levels are possible as well. Text font size and style are also controllable. There are many possible coding schemes for information presented on electronic displays. This system allows for comparison of many of the possible coding schemes. During a simulated flight, it also allows for determination of the impact of font differences on display interpretation.

2.6 DYNAMIC INFORMATION

The LCD is capable of displaying changing text information and animated graphics. Currently, plan view maps can be configured in a north-up mode with a moving airplane symbol depicting ownship position, and in a track-up mode in which an airplane symbol remains stationary and the map moves beneath it. Profile view maps can display a moving airplane that depicts distance from waypoints and altitude. The profile can either remain stationary with the airplane symbol moving over it, or it can scroll to one side with the airplane symbol moving only vertically. Airplane symbols on both map views can display predictor lines that indicate current heading and distance on the plan view and vertical speed on the profile. The method of depiction of ownship position may have an impact on how much a pilot utilizes the map for tracking purposes. It will be possible to test ownship position depiction techniques to develop optimal configurations for displays that can be used for tracking and those that should not be used for tracking.

Scale information can also be changed on command. Currently, options allow for the scale of the map to be changed with a zoom-in and zoom-out feature and the center of the display to be moved to any spot on the map using a pan feature. The display can also detect when the airplane is about to fly off of the map and make proper adjustments. Current features include an automatic zoom-out that keeps the airplane on the display screen or an automatic pan that moves the area of the map shown so that the airplane symbol remains visible. These features will be needed in the creation of a seamless map display that connects charts from all phases of flight.

Extraneous or unwanted information can be removed from any map using a declutter feature. Objects on the map can be assigned to one of five levels. Pilots can select which levels should be removed when a declutter button is pressed. Special map views and instructions may also be examined by a button press. Missed approach procedures can be indicated in both the plan and profile views.

Current paper charts vary the kinds of information displayed, e.g., detailed runway maps may be shown on one set of pages and an instrument approach chart and a break-out chart of the runway lighting system on another. This display system also has a page overlay feature that allows for the use of multiple pages of information. A smaller overlay window has been created to provide information from a briefing strip. One alternative to overlaying information is to dedicate an area on the screen for changing information. A separate area has been designated for providing the missed approach instructions, minima, notes, and remaining text or graphic information (e.g., missed approach icons). This information is available at the push of a button. Another area has been designated for providing communication and navaid frequencies. These methods of presentation of information may have a direct impact on pilot use and interpretation of the system. The flexibility designed into this display tool allows for testing a variety of presentation techniques.

2.7 INTERFACE AND AUTOMATION

All of the features built into the current display system are not needed at the same time. Selecting among the options requires a user interface. The choice of interface is another important area that must be addressed in the design of electronic charting systems. Guidelines exist for the creation of intuitive interfaces. However, these have primarily come from office environment studies and may not be practical for the cockpit. In time critical situations, a pilot may not be able to interact with a system designed for less stressful working conditions. This display system tool will allow for addressing the impact of interface design on pilot performance during stressful situations.

Automating functions provides one approach to the simplification of user interfaces. For example, communication frequencies can be selectively displayed so that only those that are needed at the moment or for the next phase of flight can be displayed. It also may be possible for the system to automatically tune the radios. Frequencies that are not in use can be stored in computer memory and displayed when needed. This feature would likely reduce display clutter and pilot confusion about radio frequencies. Automation, therefore, potentially reduces the pilot's need to interact with the system and can help the pilot think ahead.

Negative aspects of automation, however, limit what can be accomplished. Automation tends to make the system operator complacent and less situationally aware. Creating a system that can handle or anticipate all situations or that can be overridden in situations it is not equipped to handle is very difficult. The balance between user interface and automation must be explored for electronic chart systems. This balance may change according to the level of pilot and crew experience and type of aircraft. This research tool will promote an empirical evaluation of automation on pilot performance.

2.8 CHART-MAKING TOOL

In addition to the VNTSC electronic display system, there are software tools for the creation of charts. Enroute, approach, arrival and departure routes, and taxi charts can be created with this system. Full control over color coding; symbol size, position, and orientation; line weight, chart scale, text position, and text size are possible with these tools. Probe questions accompanying each chart also can be created and presented during a simulator flight. These features allow for evaluating the effect of specific charting practices, such as putting boxes around navaid frequencies and names on pilot performance.

3. RESEARCH REPORT

The data presented here are from a preliminary study of different electronic display formats for presenting non-precision Global Positioning System (GPS) instrument approaches. Pilots flew approaches in the VNTSC Frasca flight simulator which emulated a light-twin aircraft. Approaches were flown using either one of a set of different electronic chart formats designed for this study or a paper chart. Performance and subjective measures were collected. The text that follows is based on a paper presented at Aerotech '94 (see Hannon, 1994).

3.1 EXPERIMENTAL DESIGN & RATIONALE

Each electronic display format was designed to address several fundamental issues in electronic charting. These displays were not optimized, but represent a first-pass approximation based on expert opinion. The nature of this study is exploratory and the results will aid the optimization process. Three different electronic displays were designed:

1. A north-up static map resembling a paper IAP chart

2. A north-up map with a moving airplane symbol on the plan view and a horizontally scrolling profile view with a vertically moving airplane symbol

3. A tabular display listing waypoints, distances, altitudes, and headings for each leg of the approach and missed approach

All three formats were displayed in black-on-white. Illustrations of each are in Appendix B.

The first format was designed to resemble a paper IAP chart. This format was used to test the impact of electronic depiction of the same basic information as contained on paper charts. The major differences between this format and a paper chart were the location in the cockpit and the use of an electronic display screen rather than paper.

The second format used the first one as a base and added dynamic information. A moving airplane symbol was added to the plan view map to show ownship position, and the profile view map was made to scroll to the left with a vertically moving airplane symbol indicating altitude. The results of the two formats were compared to test the impact of dynamic information.

The third format presented only text information and was designed to test for the utility of profile and plan view maps for flying instrument approaches. Text information was presented in a tabular format. Each row in the table contained information for one leg of the approach. This display also utilized a smaller area of the display screen and, therefore, was designed to test the affect of reducing the overall size of the display. The results of this format were compared with the other two to test the utility of maps for flying IAPs.

Two performance measures and two subjective measures were collected during the study. The first performance measure was the pilot's flight performance. Cross-track error (XTE), airspeed, and altitude were recorded on each approach. The second performance measure was a light perimeter side-task in which pilots had to use a button on the yoke to extinguish one of four lights spaced across the instrument panel of the simulator. The lights came on, one at a time, at random times, during the approach. After fourteen seconds, a light timed out if it was not extinguished by the pilot. Response latency and accuracy were recorded. This task was designed to measure the spare attention of the pilot while flying and to detect any differences in scan pattern over the flight instruments related to the different displays. Similar tasks have been used to measure changes in spare attention (e.g., Huntley, 1973). The two subjective measures included a ten-point subjective scale of mental workload (Bedford Scale) and a post-flight questionnaire, rating each of the display formats.

Pilots flew a total of eight GPS instrument approaches, two using each of the electronic display formats and two using a paper IAP chart, depicting a GPS approach. (All eight are presented in Appendix B.) The paper charts were similar in content to the electronic displays. All of the charts were relatively uncluttered. Each approach was constructed for the study and flown into fictitious airports. All approaches were designed within FAA-Terminal Instrument Procedures (TERPS) criteria. To increase the challenge of the simulation, a moderate level of turbulence was added along with cross winds. Additionally, the missed approach procedures (MAP) were also made particularly challenging on the last approach flown using each format.

As described above, each display was designed to evaluate particular aspects of the issues involved in the design of electronic IAP charts. It was anticipated that:

- Little difference would be found between the dependent measures for the first electronic format and paper chart conditions.

- The second format, with the dynamic information, would allow for more spare attention as measured by the perimeter side-task and would be preferred by pilots to all other formats.

- Flight performance for the third format would be comparable to the paper chart condition, but spare attention might be less as measured by the perimeter side-task, mental workload higher, and subjective ratings worse than by using the paper chart.

- Systematic differences in instrument scan pattern for the different display formats would be revealed by the perimeter side-task.

3.2 EXPERIMENTAL METHOD

3.2.1 Apparatus

The VNTSC Frasca 242 flight simulator is a two-seat, fixed-base, flight simulator. All three electronic formats were presented on the LCD screen. The screen was located approximately 30 inches from the pilots. The four asterisks in Figure 1 indicate the location of the four lights used in the perimeter side-task. The luminance of each light was adjustable. The primary flight instruments were configured in the standard T arrangement. The instrument marked HSI in Figure 1 was a directional gyro (DG), with a horizontal situation indicator in the center (HSI) and a moveable heading bug. This instrument was used for course guidance on all approaches. Distance to waypoint information and the name of the current waypoint were provided to the pilot on a separate area of the display screen.

Two buttons on the left handle of the yoke were used for extinguishing the lights. The left-most button was used for the left two lights and the right-most button for the right two lights. A clip on the yoke was used to hold the paper charts. Communication between the pilots and the experimenter was established over an intercom. The pilot wore a headset and used a voice-activated microphone. To avoid interference while performing a light side task, the pilot was not required to push a button to talk.

Figures 2, 3, and 4 depict respectively the first, second, and third electronic display formats used in the study. The second format is a modification of the first. The plan view area of both formats one and two measured four inches by four inches, and the profile view measured four inches by two inches. To the right of these areas was a two-inch wide by six-inch high area that contained distance to waypoint information. The right two inches of the screen were reserved for a touch-sensitive interface that was not used in the study.

3.2.2 Subjects

Eight relatively low-time GA pilots were recruited from the local area and compensated \$10/hour for their participation. All were multi-engine and instrument-rated. Their total flight hours ranged between 200 and 3400, and the instrument hours between 100 and 400. The first three subjects were used to develop the experimental procedure, and their data were not included in the results on flight performance, the perimeter task, or subjective mental workload. The data for all eight pilots were included in the results from the subjective rating.

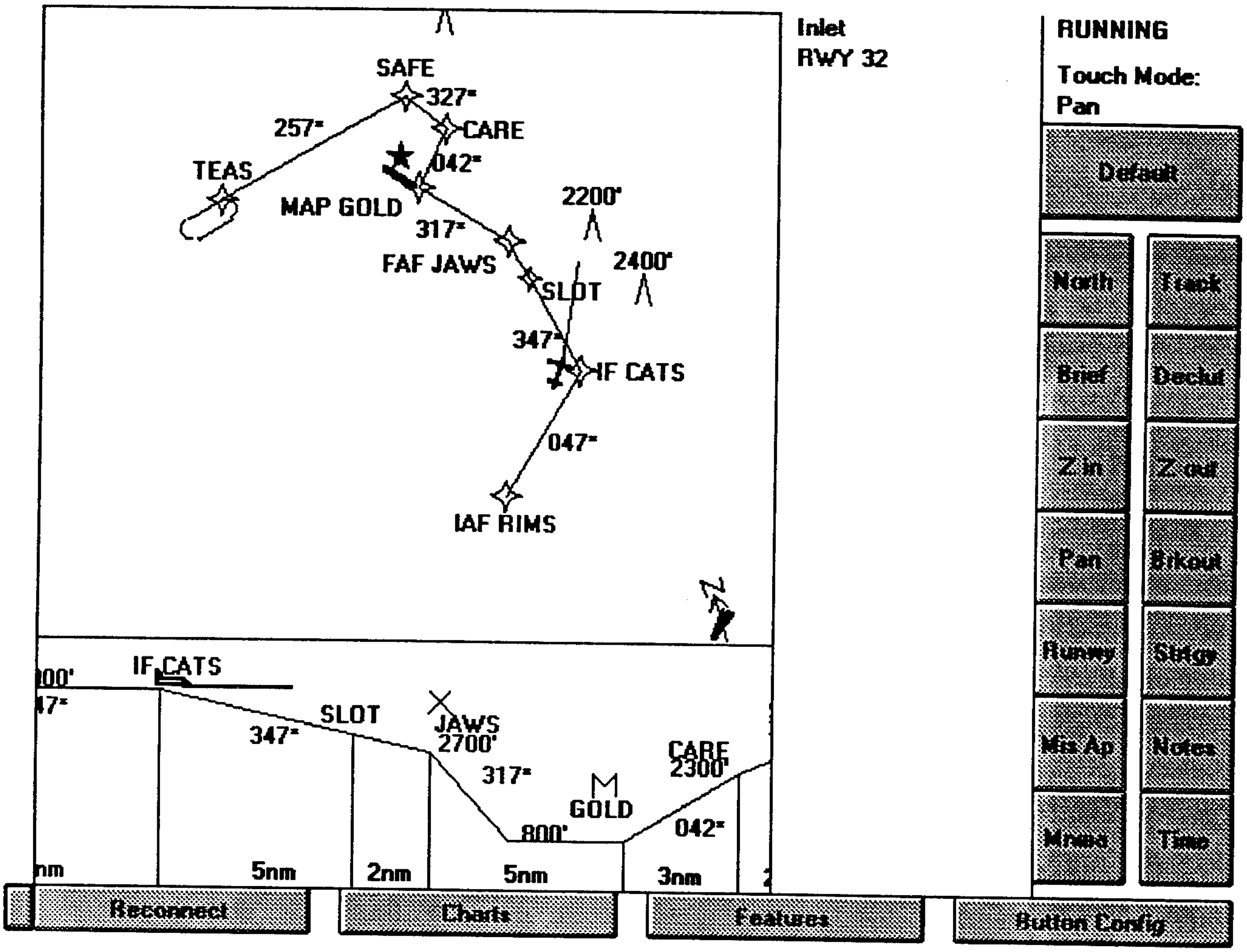


Figure 3. Dynamic Map. Moving airplane symbol added to plan and profile view maps.

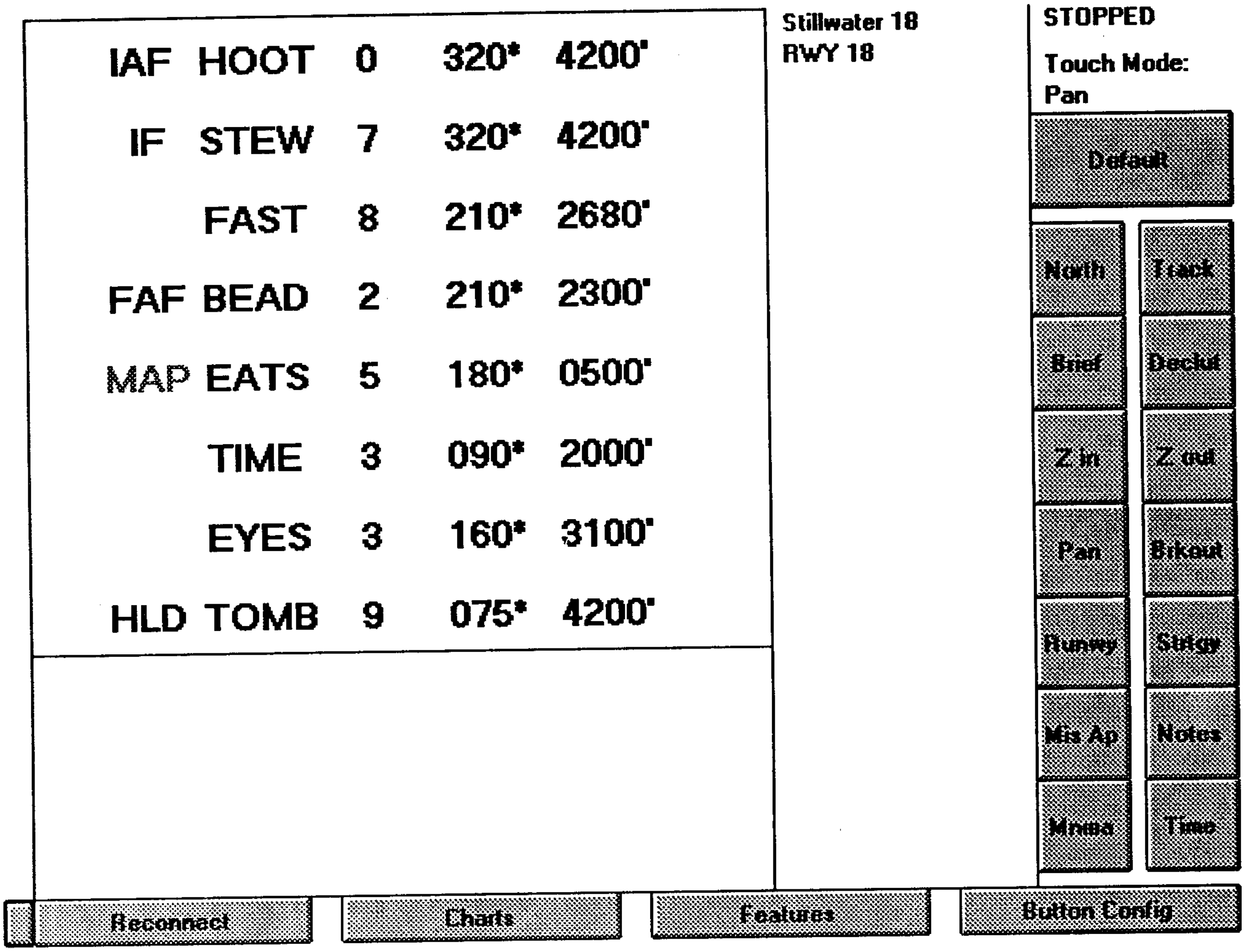


Figure 4. Tabular Display. Each row provides information for one leg of the IAP. The information does not change during the flight.

3.2.3 Procedure

Each pilot flew one approach using, in random order, each of the electronic displays and a paper chart. This same order was then repeated. Altogether, each pilot flew a total of eight approaches. Approaches were approximately 35 miles long. A different approach was flown on each trial, and each approach was unique to the type of display.

The geometry of the approaches was similar. The first leg of each started at the Initial Approach Fix (IAF) and was at a level flight to the Intermediate Fix (IF). After a turn at the IF, pilots descended to the Final Approach Fix (FAF). Two miles prior to the FAF, the needle sensitivity on the HSI changed from 1 nautical mile (nm) full scale deflection to 0.3 nm full scale deflection. After a turn at the FAF, pilots descended to the Missed Approach Point (MAP). HSI needle sensitivity returned to 1 nm full scale deflection at the MAP. The

missed approach procedures varied. On the first 4 flown, the procedure contained a 3-mile straight climb, followed by a 90-degree turn, and a shallow climb to a holding fix. On the last 4, procedures in the following order were required: a 90-degree turn at the MAP, a 3-mile climb, another turn of approximately 90 degrees, another 3-mile climb, another turn of approximately 90 degrees, and, finally, a shallow climb to a holding fix.

Pilots were instructed to fly within 10 knots on airspeed (120 knot approach speed), 100 feet on altitude, and to minimize cross track error. A radio call was required at the FAF and the MAP. Pilots were expected to fly the approach to minimums and then execute the missed approach procedure once they passed the MAP.

A typical experiment session took about four hours. Pilots were instructed on the nature of the experiment and familiarized with the simulator. The brightness of the perimeter lights of the panel were then adjusted so that they were visible when viewed directly, but did not draw attention when viewed peripherally. This insured that the subjects had to look from place to place on the instrument panel to see the lights. Pilots were then given a chance to fly the simulator and become acquainted with its performance. Once ready, pilots were prepositioned in the air at the IAF and launched on the approach. At a predetermined point prior to the holding fix, the simulation run was stopped, and the pilot was queried for a rating of mental workload. The experimenter then changed the display format in preparation for the next approach. Breaks were given as needed, typically after three or four approaches in a row had been flown. Following the last approach, pilots were asked to complete the display rating questionnaire and offer their comments and suggestions.

3.3 RESULTS

The mean results from five pilots on the last four approaches are presented in Table 1. The RMS - XTE is presented for both the final approach leg and the missed approach procedure. There is little meaningful variation on the final approach between the four displays although the dynamic display had the lowest score and the paper condition the highest. A slight increase in XTE on the missed approach is seen for the two electronic map displays, with format 1 (static) having the larger value. In practice, these differences also are not meaningful.

Table 1. Flight performance, perimeter, and workload results

	Format 1 (static)	Format 2 (dynamic)	Format 3 (text only)	Paper
XTE (miles)Final	0.132	0.094	0.116	0.157
XTE (miles)Missed	0.632	0.536	0.377	0.428
Response Latency (sec)	4.56	4.59	4.94	5.0
Response Accuracy (%)	55	49	59	49
Mental Workload	4.6	4.2	5.6	5.6

The response latency and percent correct data shown in Table 1 are averaged for the four light positions on the instrument panel. Response latency to all three electronic displays was slightly shorter than to the paper condition. Accuracy was highest for format three (text only), with format two (dynamic) and paper having equally low accuracy results. Response latency as a function of the different light positions is plotted in Figure 4 for the different display formats.[1] There are no systematic variations for the different display conditions between the four light positions. In general, response latency to the right two lights was faster than the left two and more closely grouped, with the fastest times overall recorded for the second light position.

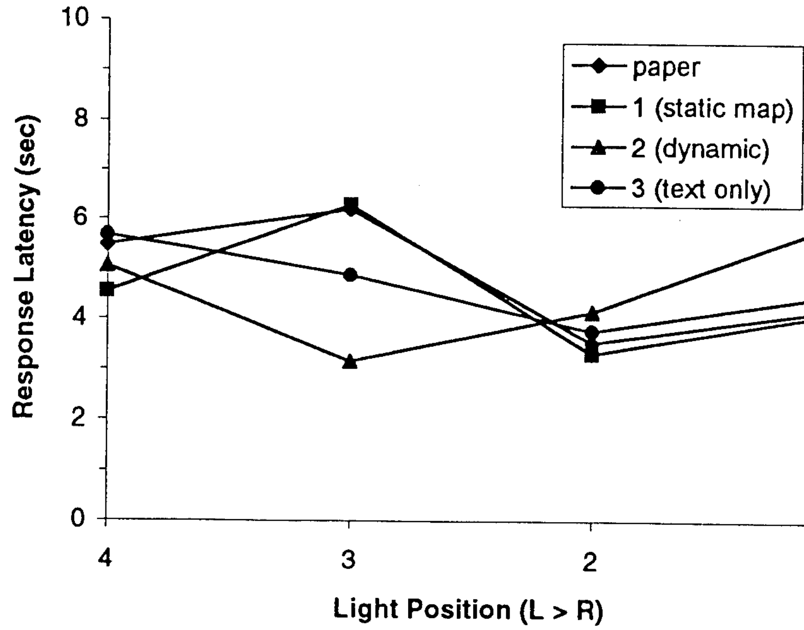


Figure 5. Response latency plotted as function of light position for each of the display formats

Accuracy data as function of light position are plotted in Figure 5. Again, there are no systematic variations between the different display conditions. Accuracy was highest, in general, for the light in position two.

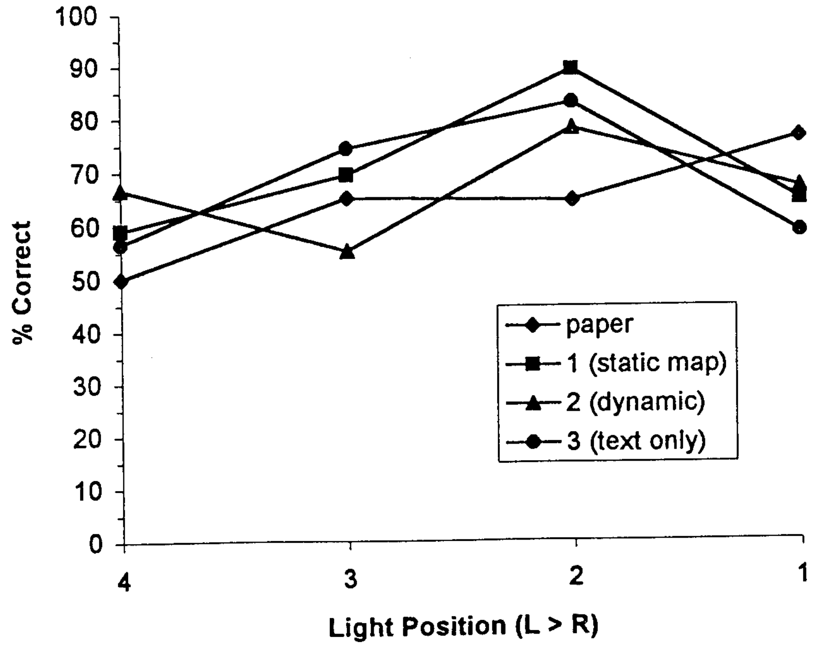


Figure 6. Response accuracy plotted as a function of light position for each of the display formats

The bottom row in Table 1 presents mental workload ratings for the four display conditions. The paper condition had the highest mental workload rating with lower values found for the three electronic displays. A Friedman analysis of variance for ranked sums did not reveal any statistically significant differences for mental workload. Plots of tracking accuracy and mental workload data are provided in Appendix A. A copy of the Bedford scale is provided in Appendix C.

Table 2 presents data from the subjective rating questionnaire for the three electronic display conditions. The questionnaire asked for responses based on a seven point scale. A value of four indicated that the electronic display in question was the same as a paper chart. Lower numeric values indicated that the electronic display was worse than paper, and higher ones indicated that it was better. On five of the six categories on which the displays were rated, the moving display received the highest scores. The text display received the highest score on the rating of readability. Wilcoxon signed rank tests were computed for ratings against a mean of 4.0. Statistically significant differences are indicated with an asterisk. Plots of subjective ratings for the three electronic formats are provided in Appendix A. A copy of the subjective rating questionnaire is provided in Appendix D.

Table 2. Subjective preference ratings

	Format 1 (static)	Format 2 (dynamic)	Format 3 (text only)
Situation Awareness	4.25	6.13*	2.25*
Workload	4.25	5.38*	4.13
Ease of Use	4.5	5.38*	3.86
Readability	3.75	4.13	5.38*
Depiction of Missed Approach	4.63	5.25*	3.38
Overall	4.38	5.44*	3.06

3.4 DISCUSSION

As predicted, the first display format condition (i.e., the static, electronic map display) yielded similar results to the paper chart condition both in terms of performance and subjective ratings. Slightly better accuracy was found on the perimeter task. This display was designed to look like the paper charts, and pilots tended to respond similarly to both. It cannot be concluded, therefore, that the depiction of IAP charts in an electronic format had a significant influence on flying the approach.

Despite the predictions, the performance results from the second display format (dynamic electronic map) also were not better than the results from the paper chart condition. In fact, the RMS XTE on the missed approach procedure, in the second format, was worse than that achieved by paper. Although the data set was too small to be conclusive, it was possible that pilots were tending to use this display as a source of information for course guidance during the missed approach.

The subjective measures for the dynamic condition were as expected. With the exception of readability, the dynamic display was rated better than paper in every category, with the highest rating for situation awareness. Given the general preference of pilots for this display, it is somewhat puzzling that the performance measures were not able to capture behavior differences between the use of this display and the paper condition. It is possible that the performance measures used here may be insensitive to the true differences. A probe question technique for information retrieval has shown significant improvements in response times for this type of display over paper charts (e.g., Hofer, 1993). Depiction of ownship position may enhance information retrieval on some probe questions by cutting down search time for relevant information. This would certainly be a benefit to situation awareness, which pilots rate the highest on this display. One pilot in this study commented that the other displays allowed more time for flying the airplane, but created less certainty in his mind about what he

was doing. Alternatively, the dynamic display increased his certainty about his actions, but he believed he was watching the display more than in the other conditions. Ultimately, this would not increase spare attention for side-tasks.

The third display format was also flown comparably to the paper condition. It cannot be concluded, however, that less spare attention was available, or that the mental workload was higher while using this display. Subjective ratings were predictably worse than for current paper charts, with situation awareness coming out quite low. This display was designed to test whether a map display was needed to fly the instrument approaches in this study. These data suggest that despite pilot objections, this type of display is sufficient to fly an instrument approach, further implying that a map display may not be necessary. After using this display, pilots generally commented that the text information separated the approach into a series of instructions that were easy to follow. There was no ambiguity about the required steps during any phase of the approach. This was true even for the complicated missed approach procedure. One pilot commented that this type of display should be incorporated into the dynamic display. It is also worth mentioning that this display format utilized a display area equal to the area of the plan view for the other two electronic formats. The fact that pilots flew successfully using this type of format suggests that instrument panel space may be conserved by considering the incorporation of some type of tabular display.

The perimeter side-task failed to detect any systematic differences in spare attention between the display conditions or to point to variations in scan pattern. Pilots appeared to perform the task easily when they had time, but quickly ignored it as they became busy during the approach. This was evident from the fact that over 95 percent of the incorrect responses came from light presentations that had timed out. That is, the lights went on and off without the pilot noticing them at all. The overall patterns of response times and accuracies emerged as expected, with faster response times and higher accuracies for the position two light than for the others. Since distance to waypoint information was located to the far right of the first light position, it was expected that the scan pattern would be shifted to the right. Comparable results would have been expected for lights two and three if the scan had been evenly distributed. Lower accuracies and higher response times were found, in general, for light position four than position one. This is understandable since there was nothing of interest for the pilot to look at in the vicinity of position four and detection of it required a special effort to look in its direction.

Pilots generally liked the electronic displays because they were incorporated into the instrument panel. Fatigue from having to change accommodation planes to view paper charts was noted as a problem. The larger type used on the electronic displays was also preferred, although the graphics techniques utilized on paper charts made for a less ambiguous presentation in some instances. A few pilots complained that waypoint names were harder to identify with a waypoint symbol on the electronic charts than on paper. The boxes and line segments often used on paper charts did not show clearly on these electronic charts and were omitted. All pilots liked the vertical guidance provided on the profile view of the dynamic display. One commented that the profile alone was sufficient to fly the approach.

A few pilots commented that they would have liked more time to work with each of the displays. Pilots had the opportunity to use each display only two times and between the two times three other display formats were used. This made it difficult to learn the nuances of each display and use them to their advantage. This factor is both a strength and a weakness of the study. Greater behavioral differences may have been obtained with longer exposures to each of the displays. However, the fact that all of the approaches were flown successfully with all of the displays indicates that they are all reasonably easy to use. A larger sample size, however, is needed before solid conclusions can be drawn from this research.

Future development will build on the current displays. Color coding of the information and track-up map orientations will be included in future studies. Color has been shown to enhance information retrieval (Mykityshyn, Kuchar, and Hansman,1994), but it is not clear whether color coding will influence flight performance.

Track-up displays have been shown to produce better performance on some tasks than north-up displays. However, pilots do not prefer track-up displays. This orientation of the chart may have a negative effect on spare attention. The impact of the size of the display presents another issue for future studies. The screen used here is clearly too large to fit into most GA cockpits. The map displays are likely to become less effective as the display size is reduced, creating a clear advantage for the text-only display, or a hybrid combination of text and maps.

4. FUTURE DIRECTIONS

The suggestions we have received from pilots on the electronic chart displays that we have developed, in addition to our empirical findings and the general human factors issues noted above, have led to the creation of new electronic chart designs. Three prototype displays are currently being tested and fine-tuned and will receive empirical evaluation in the future. A description of each of the new electronic chart design concepts is discussed below.

4.1 DYNAMIC TEXT

One of the most interesting findings in this study is that the third display format, using only a tabular display of IAP information, resulted in acceptable flight performance in the simulator. This format was developed, in part, to explore the necessity of using maps for presenting procedural information. The table was static, that is, all of the information was continuously present and did not change during the flight. In general, pilots commented that this third format provided an unambiguous interpretation of the instrument approach and missed approach procedures. Although this format used a smaller display screen area than either of the two formats that used maps, the alphanumerics were fairly large and pilots rated this type of display as very easy to read. Several pilots, however, commented that the organization of the display was potentially confusing. During the approach it was difficult to remember what line to read in the table. It also was confusing to have the numeric data following the name of the waypoint. With the waypoint name first in the row, some pilots initially thought the quantitative information applied to the leg of the approach following the waypoint (i.e., from the waypoint). A new table design was created to address these limitations (see Figure 7).

Crs	Dis	Alt	Name	Type
193	5.30	2300	FAST	FAF
163	5.00	0900	BEAD	MAP
073	3.00	2000	EATS	
143	3.00	3100	TIME	
058	9.00	4200	EYES	

Figure 7. Dynamic Text. Tabular display of approach course information. Top line of table counts down the distance to the waypoint. The table scrolls upwards as each leg of the approach is completed.

In the new table format the columns of data were rearranged so that quantitative information precedes the name of the waypoint in any row of the table (i.e., leg of the approach). It is anticipated that this organization will facilitate the interpretation of the procedure since the quantitative data provides the information required for flying to the waypoint. For example, the top row in Figure 6 reads: a course of 180 degrees, distance of 10 nm, down to a target altitude of 4400 feet to the waypoint COOK. Titles were added at the top of the table over each column to further facilitate the interpretation of the information.

The entire table is also dynamic. The top row in the table presents the information for the current leg of the approach. Information for a leg is removed from the top of the table once the waypoint is passed (i.e., it is no longer needed), and the information for all remaining legs is scrolled upwards. With this format, the top row of the table is always the current leg of

the approach. Pilots no longer have to search for the appropriate row in the table for current waypoint information. The remaining data can be previewed for briefing subsequent legs of the approach, such as the missed approach procedure. In addition to the removal of unneeded information, the distance information to the current waypoint has been changed to a digital counter that counts down the distance to the waypoint. All of these modifications should enhance the utility of the tabular display of IAP information.

Future research with this display format will assess the effect of a tabular format for presenting IAP information. Tabular displays can fit on smaller display screen areas than formats with a combination of text and graphics, provided that all of the information is clearly readable. Tabular data can also be presented on display screens of a lower resolution than graphical information. These advantages alone suggest that there is a role in the cockpit for a separate display of tabular information for flying instrument approaches. How pilots will use these displays and what information should be presented must still be determined.

Novice pilots may find that IAPs are easier to interpret using the table than a map, particularly for unfamiliar airports. More experienced pilots may prefer the table because they can easily select key pieces of information from it. The columnar arrangement also provides additional information that pilots may learn to use. For example, the magnitude of a descent on a given leg is easy to determine by comparing the target altitude at the waypoint with the altitude above it in the table. However, additional information such as current altitude or vertical speed may be required to fully utilize all of the information available in the table. Improvements to the format will emerge as a role for the tabular display becomes defined.

4.2 HYBRID MAP AND TABULAR FORMAT

One of the biggest disadvantages of the tabular display is its failure to provide the pilot with good situation awareness. The subjective data reported in Section 3, "Research Report," support this fact. A map display seems to be required for providing pilots with a level of confidence about their surroundings. The difficulty in providing a map display to the pilot is that the combination of text and graphics typically presented on an IAP chart requires a certain amount of display resolution and, therefore, a certain size, for clear visibility. Although new aircraft may be designed with sufficient space in the instrument panel to hold the required display screens, existing aircraft will require a retro-fit of the display into an area of limited space. Therefore, there will be advantages to map displays that will fit into small spaces. Research is needed to determine how small a map can be and still be useful to the pilot. This is more than a matter of shrinking existing map displays. Resolution limits on electronic displays will require that some information be removed and other be presented in a different form. The format presented in Figure 8 was created to address this issue.

The map area in Figure 8 presents a plan view illustration of the approach. Individual legs of the approach are shown scaled to the display area, at their correct orientations. The magnitude of the turns is also displayed correctly. Waypoints are identified by circles at the

terminal points of the legs of the approach. The FAF and MAP are continuously identified with text labels. Aircraft position on the map can be displayed continuously, with a trail indicating the history of the airplane on the approach. At the top of the display, two lines of tabular data are available. The top line provides data <u>to</u> the current waypoint. The second line provides information <u>to</u> the subsequent waypoint. The tabular data is organized in the same way as the information in Figure 7, and the distance information to the current waypoint counts down as the waypoint is approached. A plan-brief feature (not shown) is provided to the pilot that allows for the previewing of the approach. Successive button presses provide information on the map of waypoint names for each leg of the approach. Corresponding data for the beginning and ending waypoints of a leg appear in the tabular display above the map. The size of the map can be adjusted up and down.

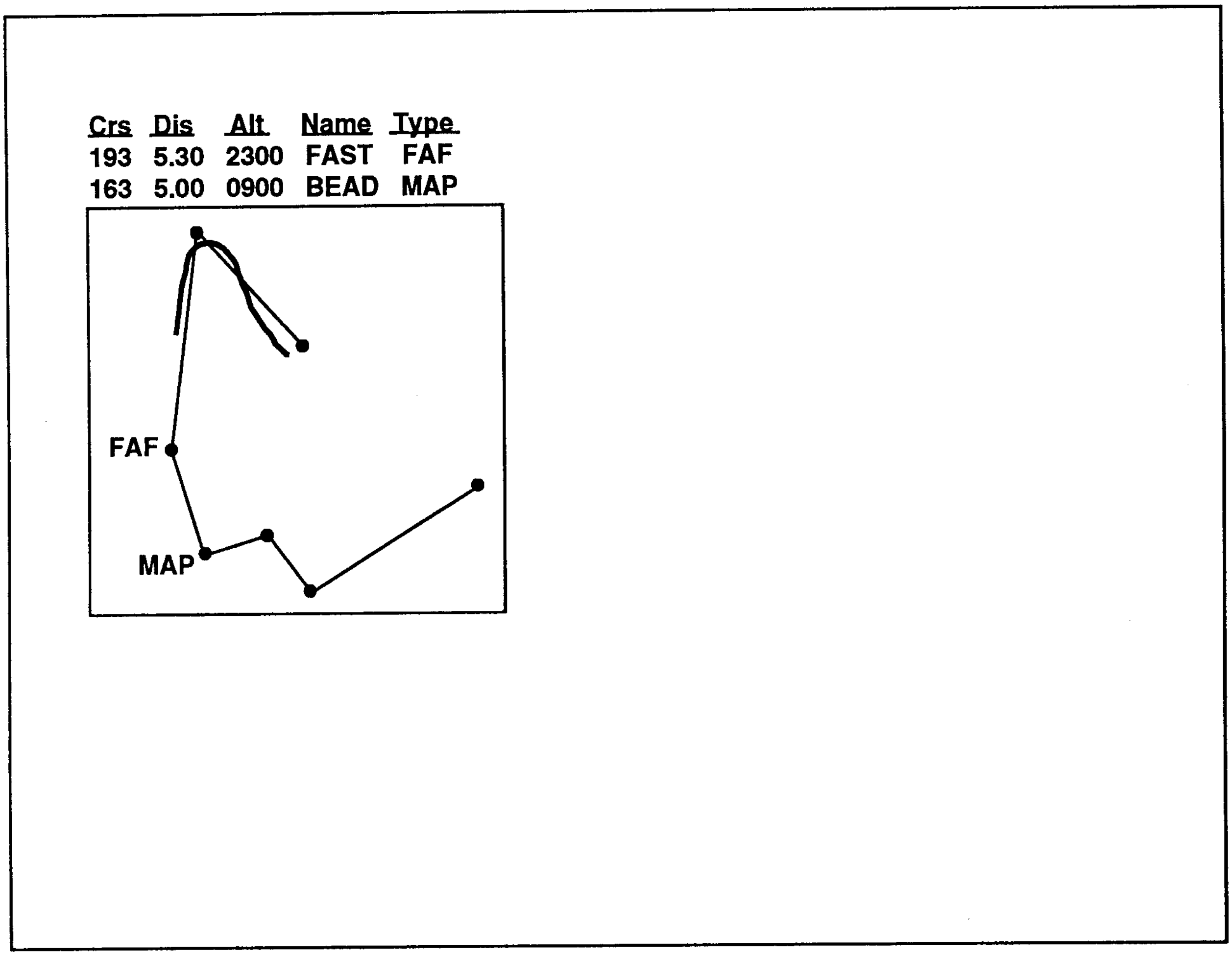


Figure 8. Hybrid Map and Tabular Format. Plan view map with schematic of approach course, minimal text, and flight track. Two lines of text provide information for current waypoint and next waypoint.

The display in Figure 8 was designed to test specific issues in electronic chart development. First, the size of the map has been adjusted so that the utility of small map displays can be assessed. With the removal of much of the text from the map, there is also an issue of the interpretation of information that has been divided between the plan-view map and the table. It may be concluded that minimal text on the map display is necessary for maintaining situation awareness. It is anticipated that the small size of the map will also discourage pilots from attempting to use the map for course guidance. Remaining issues to be resolved are the incorporation of extra information such as minima, notes, runway maps, and runway lighting systems. These limitations, however, do not detract from the basic concept of this design.

4.3 LINEAR MAP

Changing the appearance of the graphics provides an alternative solution to the problem of the size limitations of electronic charts that contain both graphics and text. The approach course can be straightened and transformed into a vertical line. Along the line, waypoint names and symbols can denote the leg lengths, and turn vector symbols at the waypoints can indicate the direction and magnitude of the turns. Accompanying text can be placed along the vertical line indicating altitudes, headings, leg lengths, and waypoint identifiers. The position along the course can be presented by a cursor moving up the line. A display of this design is presented in Figure 9.[2]

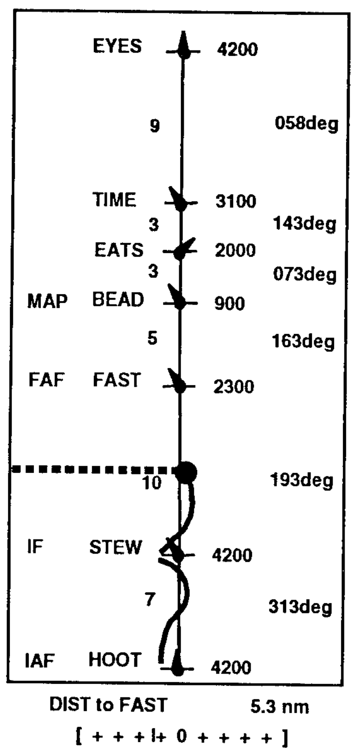


Figure 9. Linear Map. Vertical line indicates course; distance between waypoints, waypoint names, and identifiers are to the left; target altitudes and headings are provided to the right. The track relative to the center line is shown, with the horizontal line providing current position. A CDI is provided at the bottom of the display.

The main advantage of the linear map display is the reduction of the graphics to a single vertical line. This line is easily displayed on relatively low resolution display screens. Additionally, the area on the screen that is usually consumed by the complex geometry of the approach course has been reduced. This format, therefore, is able to fit on a fairly narrow display screen. Much of the text and graphical information presented on conventional maps is preserved with this design. A further advantage includes the fact that the vertical alignment of the course creates a track-up perspective for each leg of the approach. This orientation will be advantageous for monitoring cross-track position. The altered form of the map display does not promote situation awareness, however, and terrain depiction is not possible. Preliminary investigation also indicates that it is difficult to use the display during turns and that it is difficult to predict the path of the position cursor through a turn. Further design evaluation is needed to optimize this display.

5. NOTES

1. The response latency and accuracy data for the perimeter task are averaged over all five subjects. The stochastic nature of the perimeter side-task created uneven samples for the different light positions across the different display conditions. For this reason, a group average was reported. Caution should be used in any attempt to generalize from these data.

2. Steve Robinson, of NASA Langley, provided the concept and design for the linear map.

REFERENCES

Aretz, A. J. (1991). "The Design of Electronic Map Displays." *Human Factors*, 33(1), pp. 85-101.

Clay, M. (1994). *Resource Document for the Design and Certification of Electronic Instrument Approach Procedure Displays - Final Report.* Prepared for VNTSC by Monterey Technologies, Inc.

Clay, M. (1993). *Cognitive Handbook for the Design of Electronic Displays of Instrument Approach Procedure Charts. - Interim Report.* Prepared for VNTSC by Monterey Technologies, Inc.

Endsley, M. R. (1993). "A Survey of Situation Awareness Requirements in Air-to-Air Combat Fighters." *The International Journal of Aviation Psychology*, 3(2), pp. 157-168.

Endsley, M. R. (1993). *Situation Awareness in Dynamic Human Decision Making: Measurement.* Proceedings of the First International Conference on Situational Awareness in Complex Systems, Orlando, FL.

Hannon, D. J. (1994). *Effects of a Moving Map Display on Pilot Performance on Instrument Approach Procedures.* Paper presented at the Society of Automotive Engineers Aerotech '94 meeting, Los Angeles, CA.

Haskell, I. D., Wickens, C. D. (1993). "Two- and Three-Dimensional Displays for Aviation: A Theoretical and Empirical Comparison." *The International Journal of Aviation Psychology*, 3(2), pp. 87-109.

Hofer, E. F., Palen, L. A., Higman, K. N., Infield, S. E., & Possolo, A. (1992). *Flight Deck Information Management - Phase II, Final Report to the FAA on Contract DTFA01-90-C-00055.* Boeing Commercial Airplane Group Document No. D6-56305-1.

Hofer, E. F. (1993). *Flight Deck Information Management - Phase III, Final Report to the FAA on Contract DTFA01-90-C00055.*

Huntley, M. S. (1973). "Effects of Alcohol and Fixation-Task Difficulty on Choice Reaction Time to Extrafoveal Stimulation." *Quarterly Journal of Studies on Alcohol*, 34(1), pp. 89-103.

Marshak, W. P., Kuperman, G., Ramsey, E. G., Wilson, D. (1987). *Situational Awareness In Map Displays.* Proceedings of the Human Factors Society - 31st Annual Meeting, pp. 533-535.

Mykityshyn, M. G., Kuchar, J. K., & Hansman, R. J. (1994). "Experimental Study of

Electronically Based Instrument Approach Plates." *The International Journal of Aviation Psychology*, 4(2), pp. 141-166.

Ricks, W. R., Jonsson, J. E., & Barry, J. S. (1994). *Managing Approach Plate Information Study (MAPLIST): An Information Requirements Analysis for Approach Chart Use.* Paper presented at the Society of Automotive Engineers Aerotech '94 meeting, Los Angeles, CA.

Smallman & Boynton (1990). "On the Usefulness of Basic Colour Coding in an Information Display." *Displays*, 14(3), pp. 158-165.

Wickens, C. D., Liang, C., Prevett, T., Olmos, O. (1994). *Egocentric and Exocentric Displays for Terminal Area Navigation.* University of Illinois Institute of Aviation Technical Report (ARL-94-1/NASA-94-1). Savoy, IL: Aviation Research Laboratory.

APPENDIX A

Tracking Performance Data

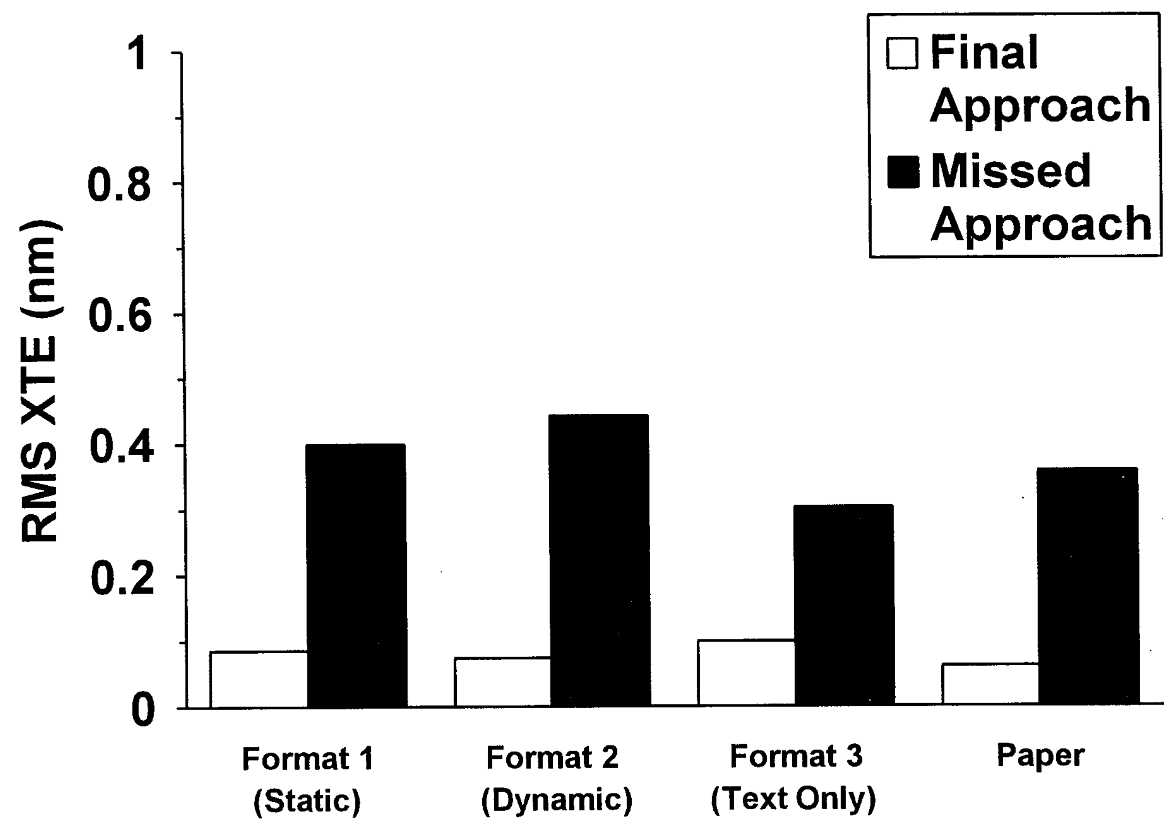


Figure A-1. Plot of RMS cross-track error as a function of the display format. Open bars are for final approach, filled bars are for the missed approach procedure.

Subjective Mental Workload

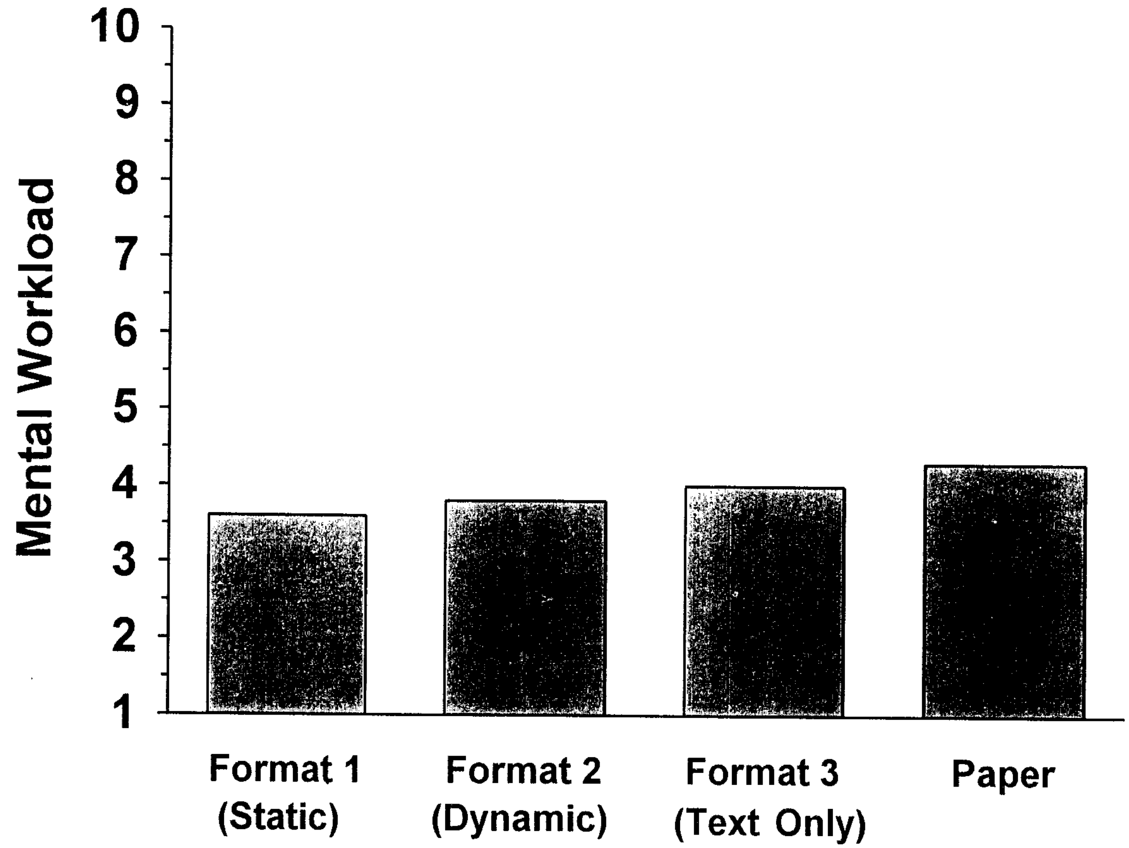


Figure A-2. Plot of mental workload from Bedford Scale as a function of display format.

Subjective Ratings

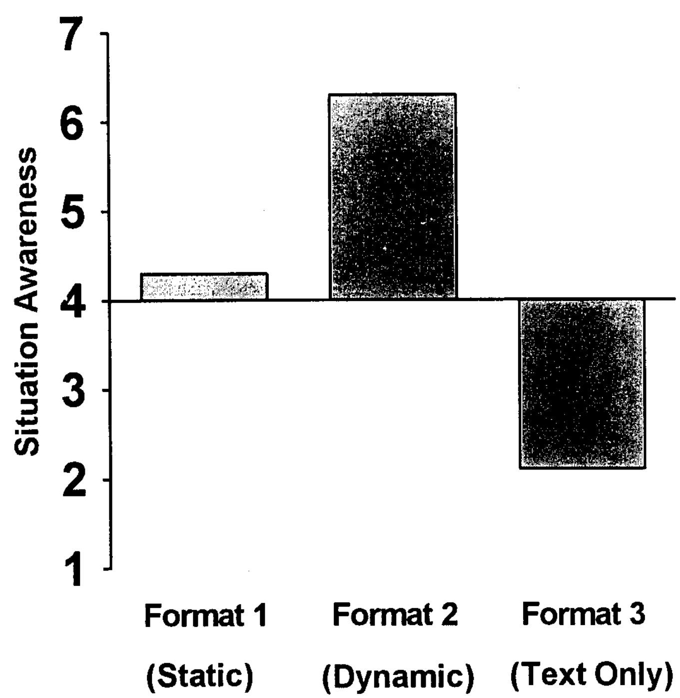


Figure A-3. Subjective rating of situation awareness as a function of electronic display format. Ratings greater than 4 mean the display is better than paper charts.

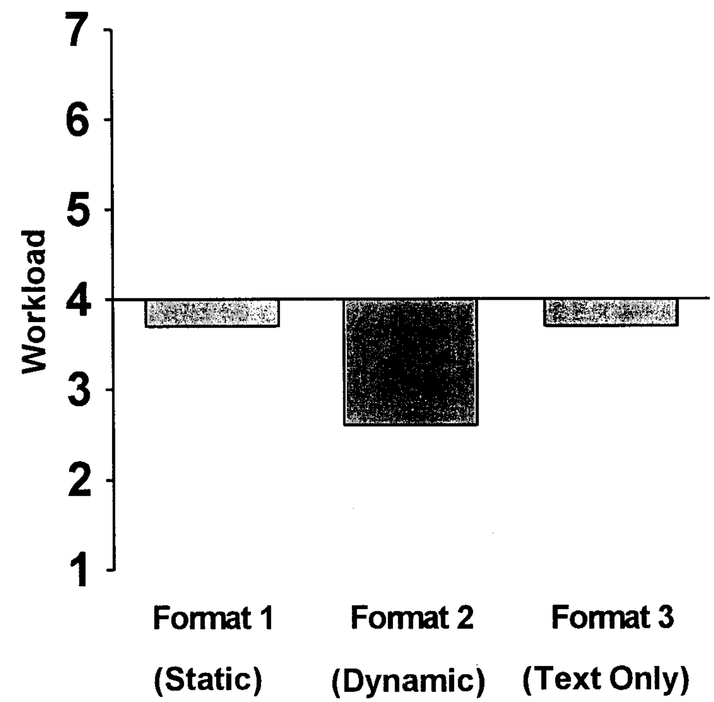


Figure A-4. Subjective rating of workload as a function of display format. Ratings lower than 4 mean the display has a lower workload than paper charts.

Subjective Ratings

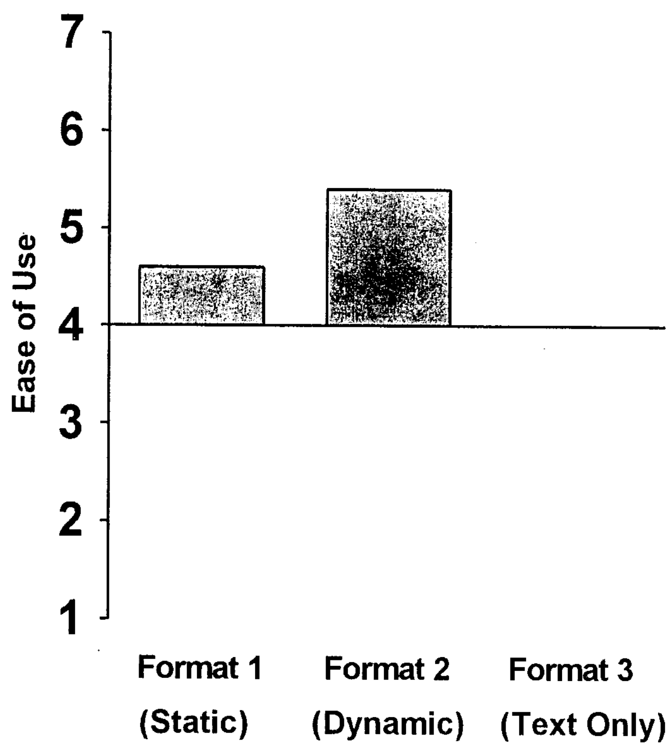


Figure A-5. Subjective rating of ease of use as a function of electronic display format. Ratings greater than 4 mean the display is better than paper charts.

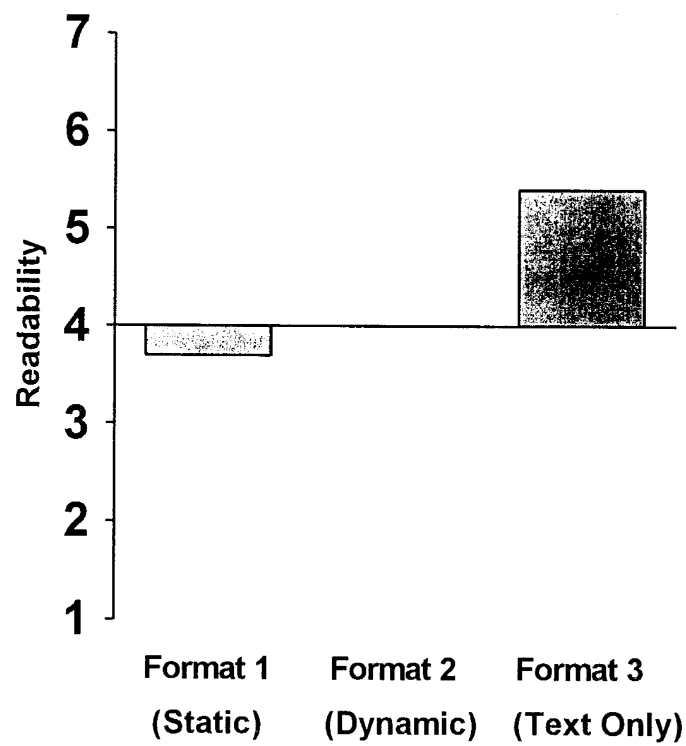


Figure A-6. Subjective rating of readability as a function of electronic display format. Ratings greater than 4 mean the display is better than paper charts.

Subjective Ratings

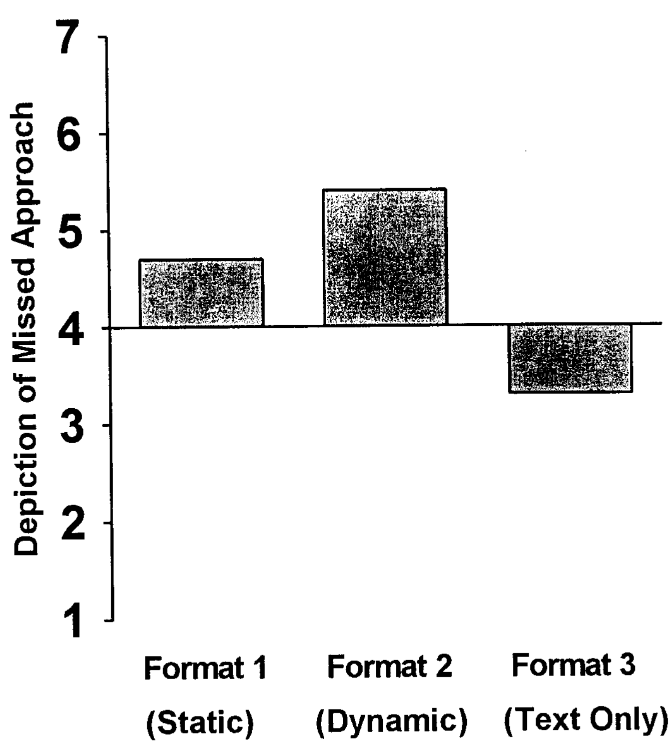


Figure A-7. Subjective rating of depiction of the missed approach procedure as a function of electronic display format. Ratings greater than 4 mean the display is better than paper charts.

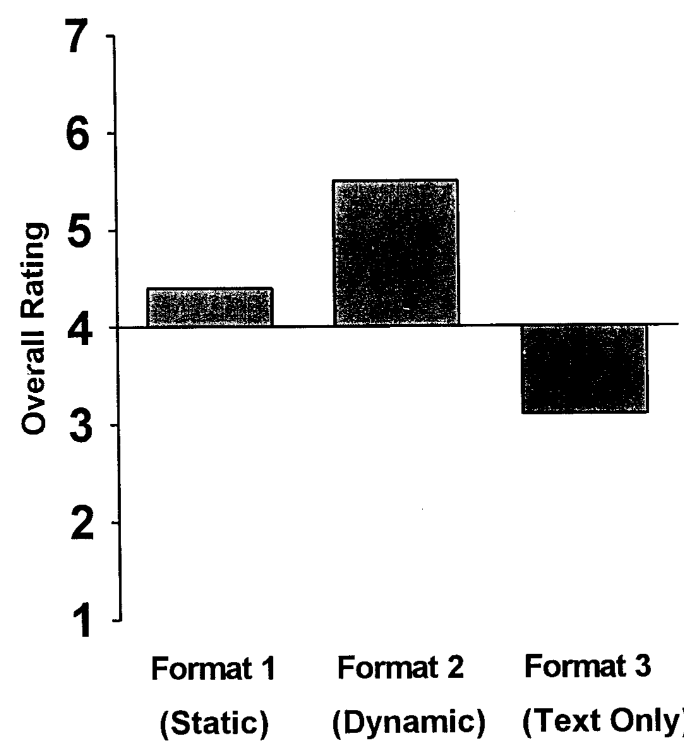
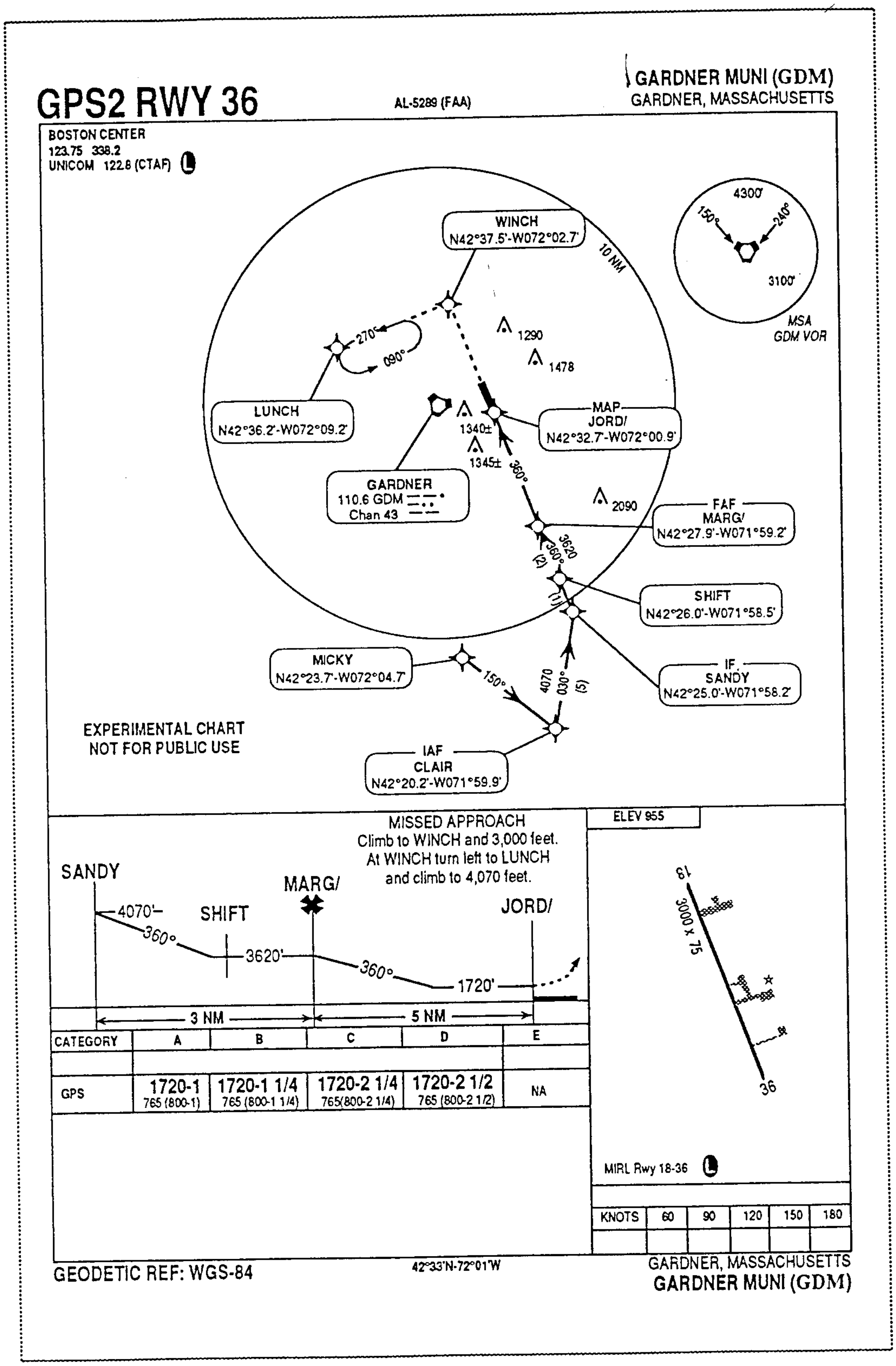
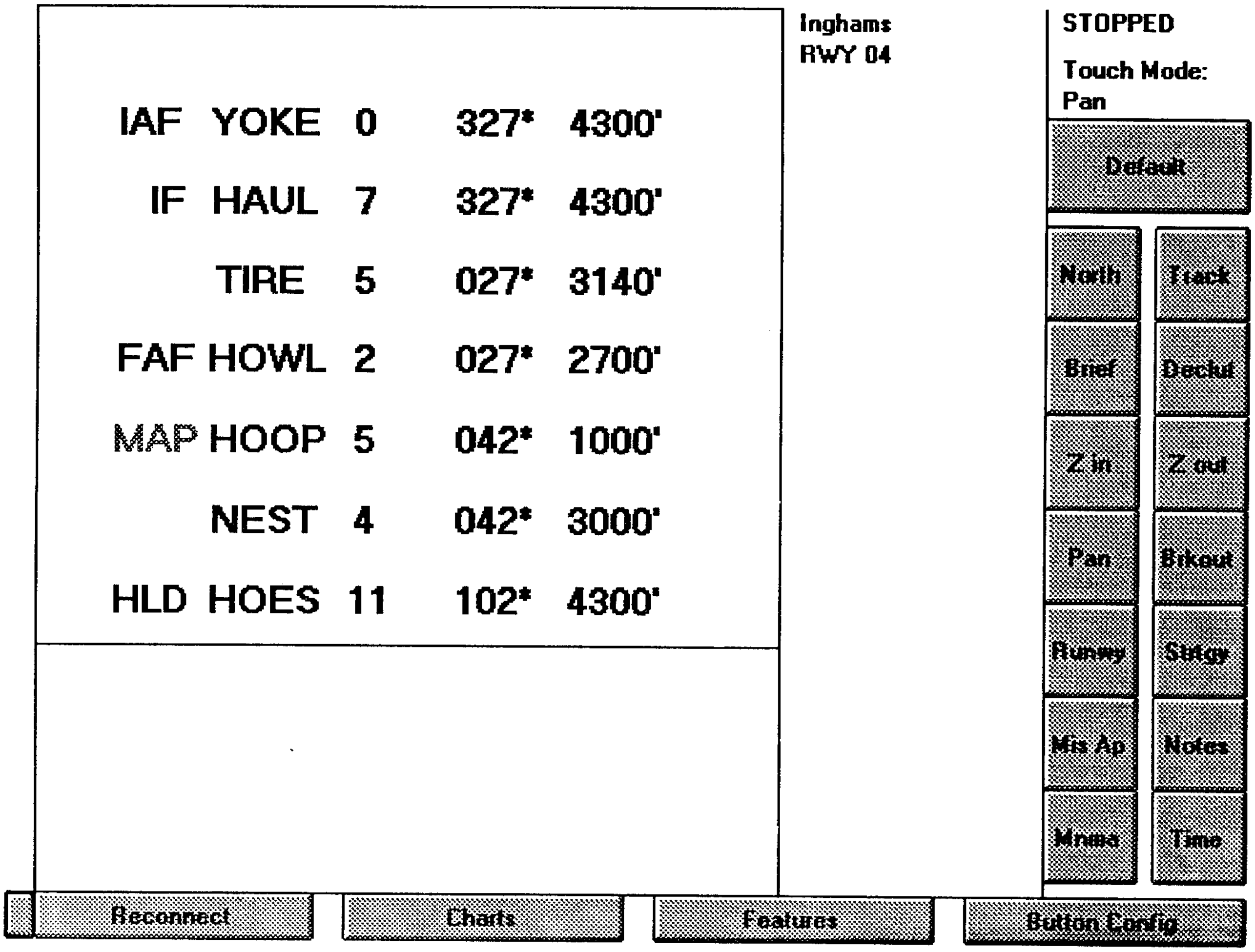


Figure A-8. Overall subjective rating as a function of electronic display format. Ratings greater than 4 mean the display is better than paper charts.

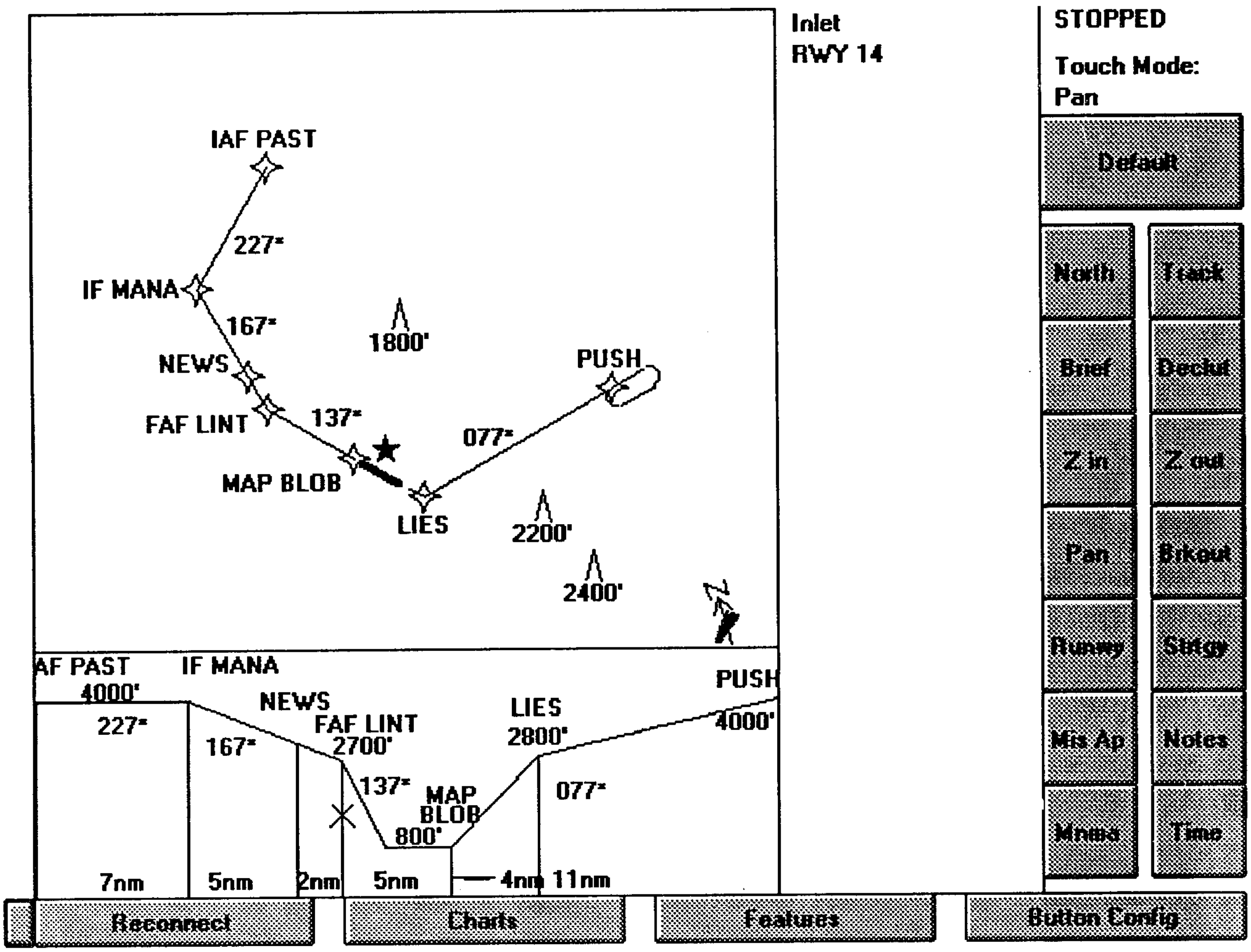
APPENDIX B



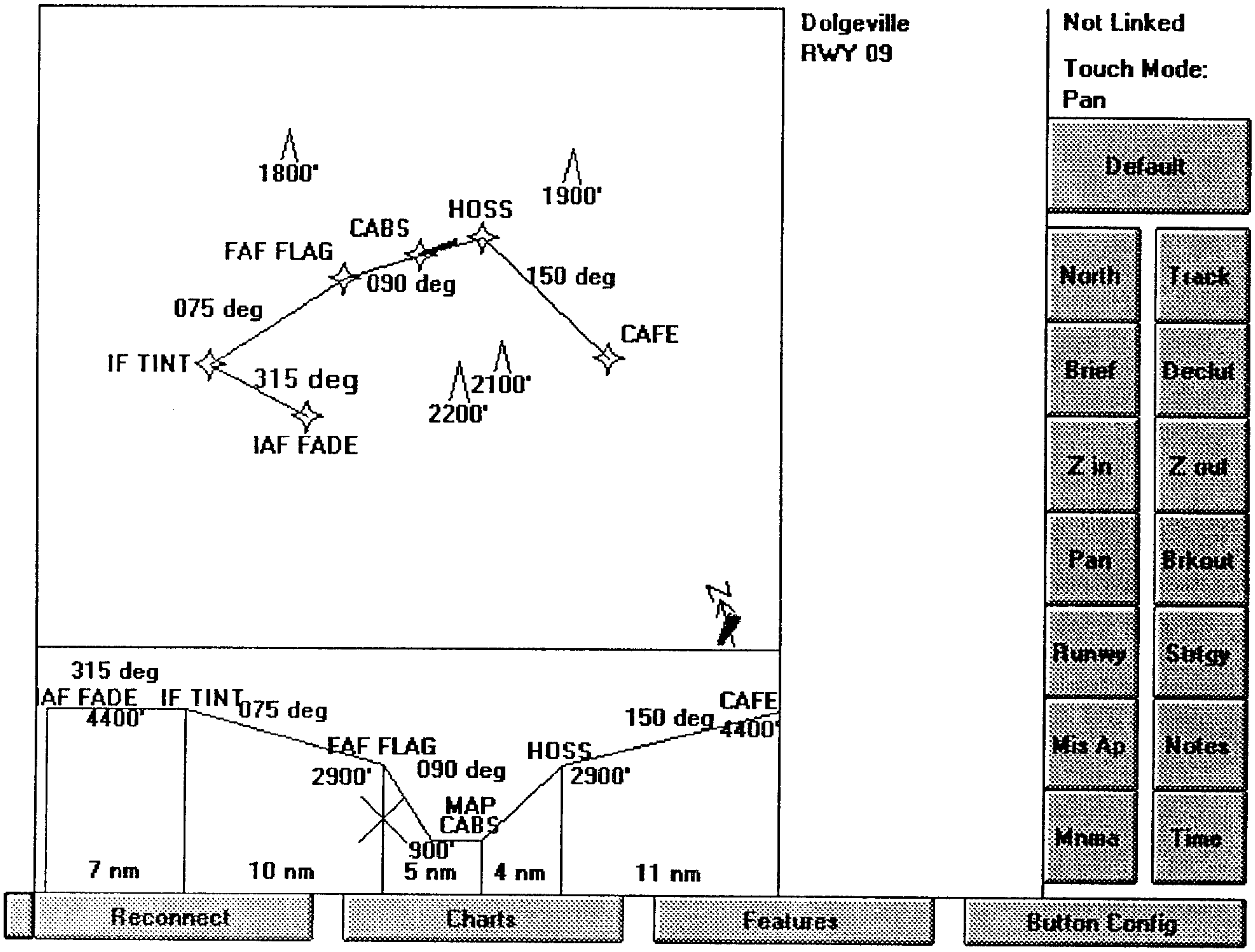
B-1. Experimental non-precision GPS approach for GARDNER RWY 36



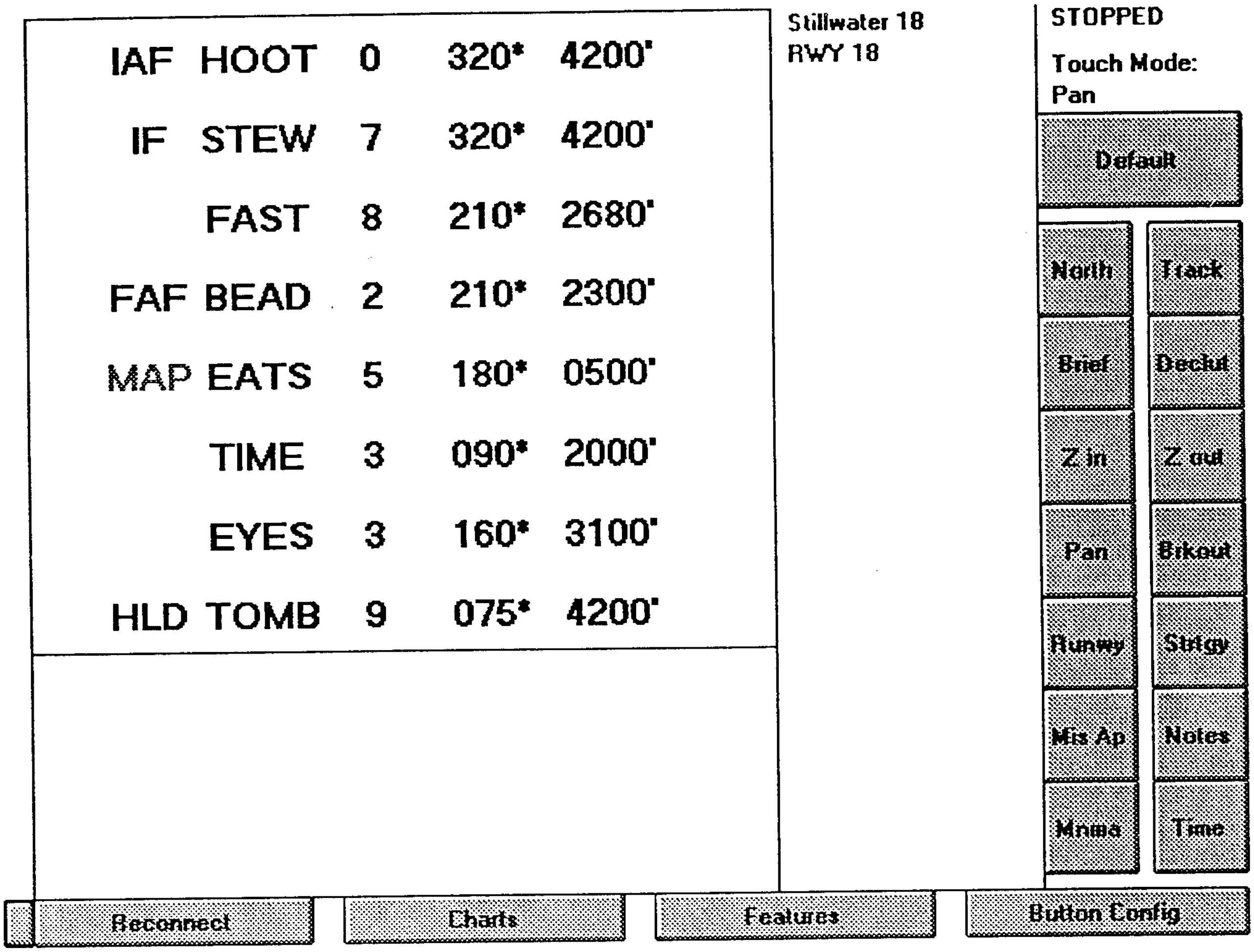
B-2. Experimental non-precision GPS approach for INGHAMS RWY 04



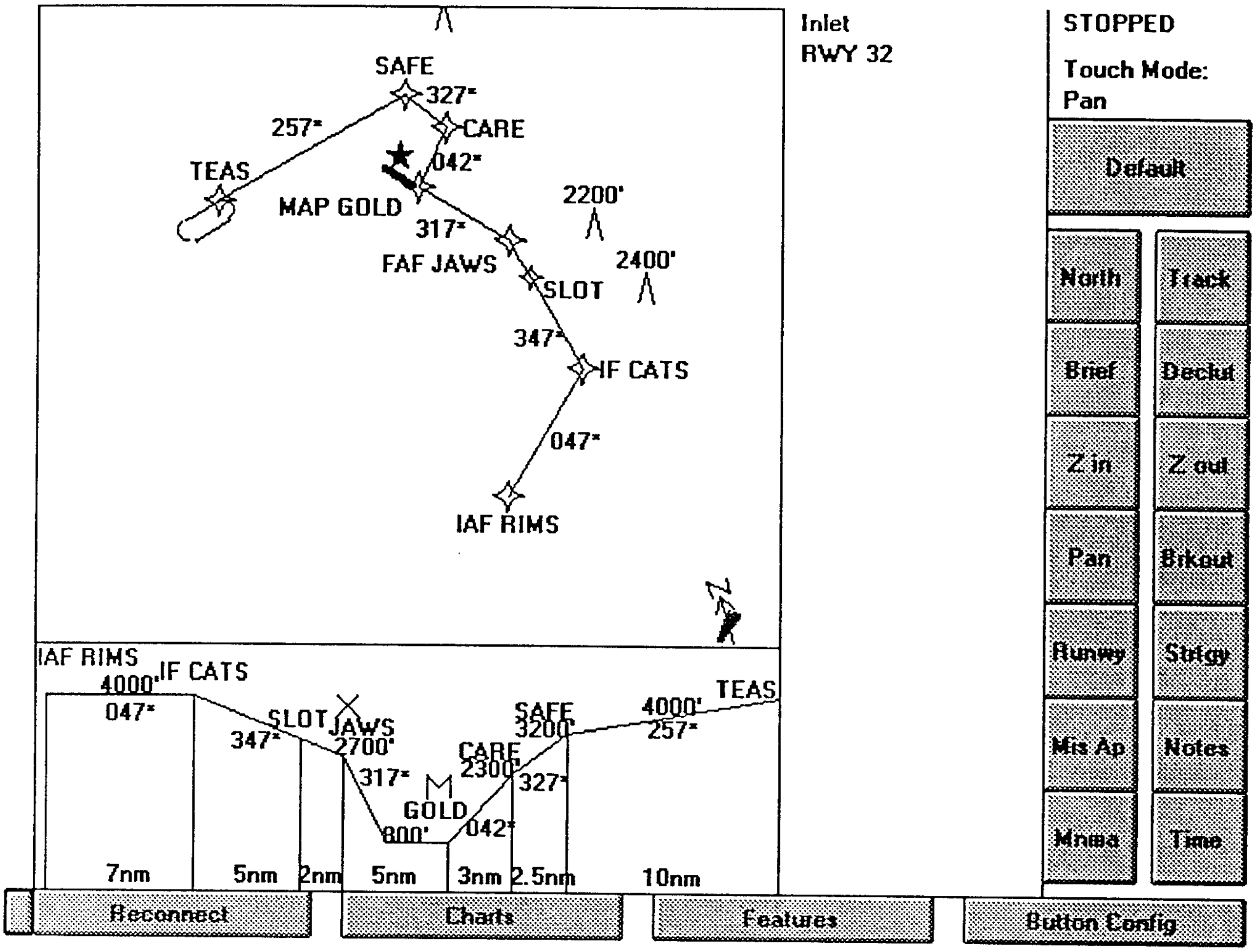
B-3. Experimental non-precision GPS approach for INLET RWY 14



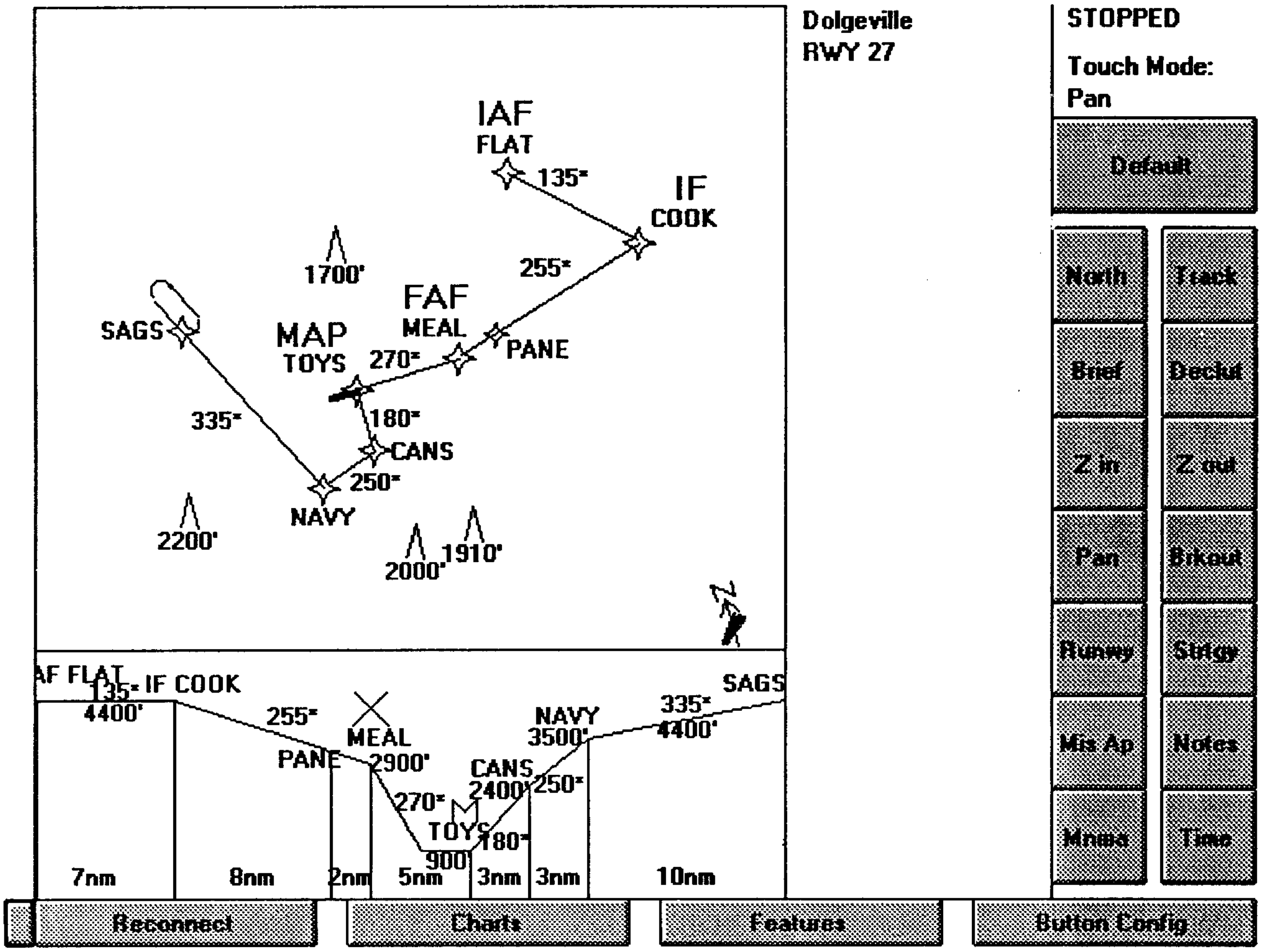
B-4. Experimental non-precision GPS approach for DOLGEVILLE RWY 09



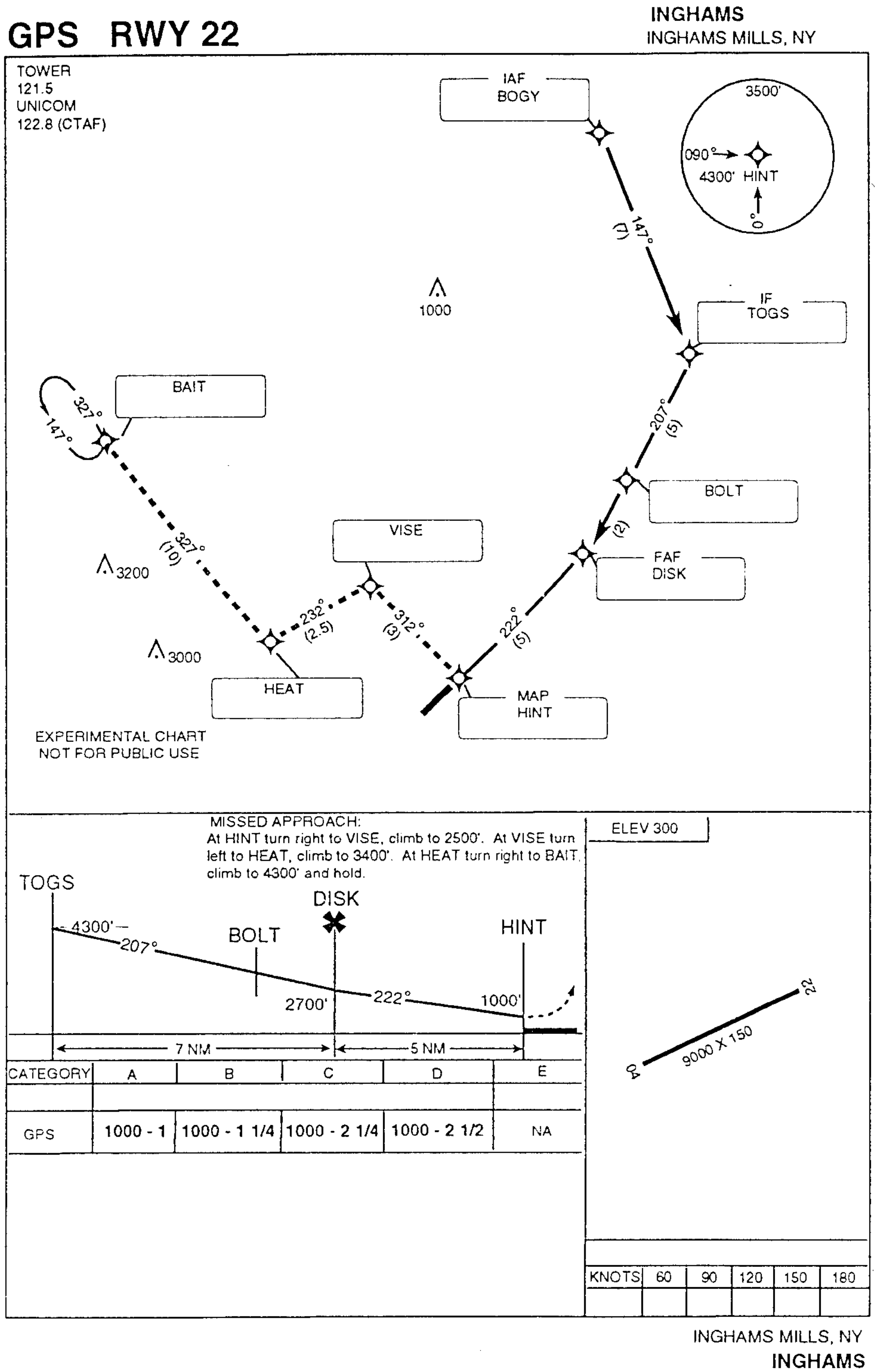
B-5. Experimental non-precision GPS approach for STILLWATER RWY 18



B-6. Experimental non-precision GPS approach for INLET RWY 32

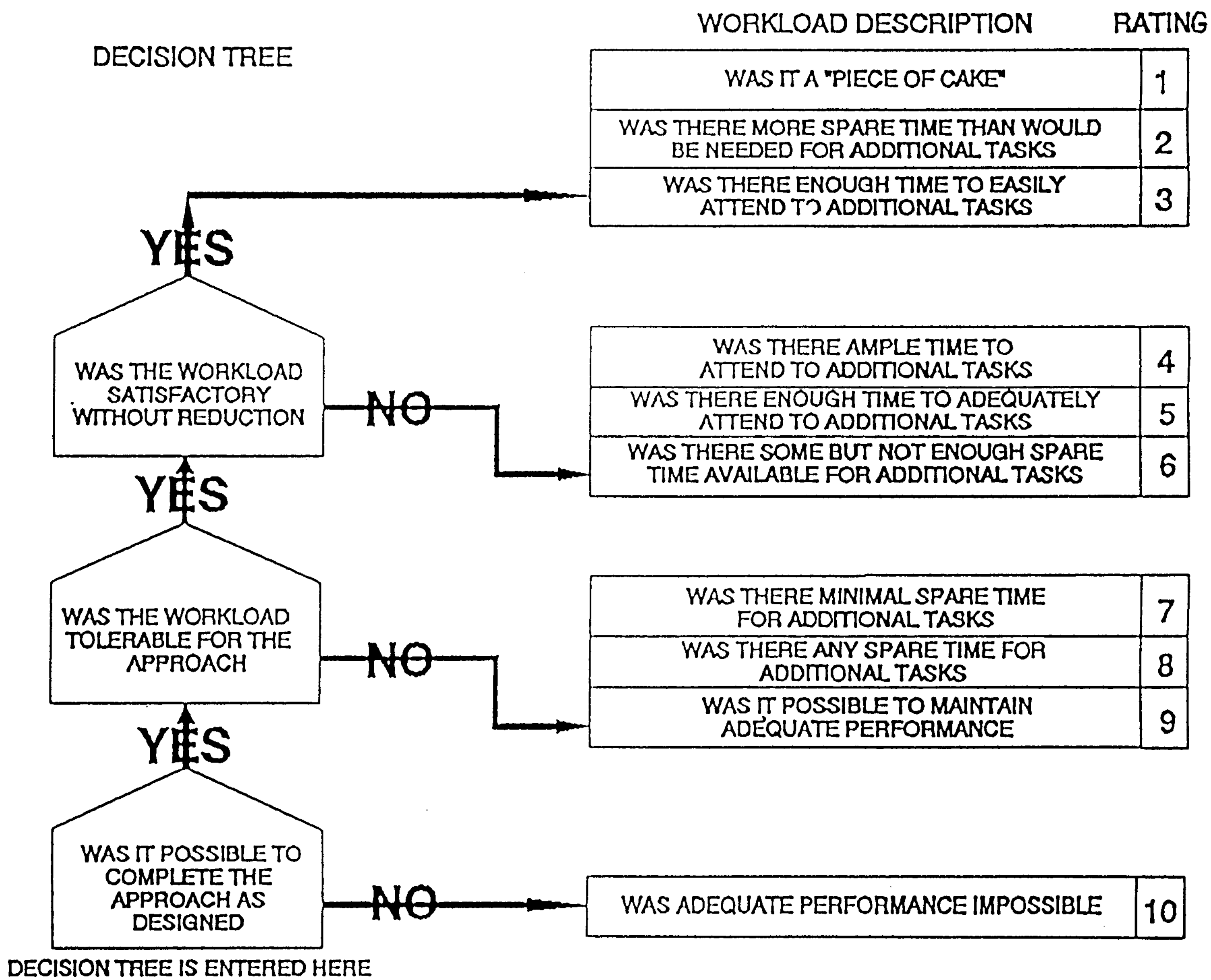


B-7. Experimental non-precision GPS approach for DOLGEVILLE RWY 27



B-8. Experimental non-precision GPS approach for INGHAMS RWY 22

APPENDIX C


DECISION TREE
WORKLOAD DESCRIPTION
RATING
WAS IT A "PIECE OF CAKE"
1
WAS THERE MORE SPARE TIME THAN WOULD BE NEEDED FOR ADDITIONAL TASKS
2
WAS THERE ENOUGH TIME TO EASILY ATTEND TO ADDITIONAL TASKS
3
YES
WAS THE WORKLOAD SATISFACTORY WITHOUT REDUCTION
NO
WAS THERE AMPLE TIME TO ATTEND TO ADDITIONAL TASKS
4
WAS THERE ENOUGH TIME TO ADEQUATELY ATTEND TO ADDITIONAL TASKS
5
WAS THERE SOME BUT NOT ENOUGH SPARE TIME AVAILABLE FOR ADDITIONAL TASKS
6
YES
WAS THE WORKLOAD TOLERABLE FOR THE APPROACH
NO
WAS THERE MINIMAL SPARE TIME FOR ADDITIONAL TASKS
7
WAS THERE ANY SPARE TIME FOR ADDITIONAL TASKS
8
WAS IT POSSIBLE TO MAINTAIN ADEQUATE PERFORMANCE
9
YES
WAS IT POSSIBLE TO COMPLETE THE APPROACH AS DESIGNED
NO
WAS ADEQUATE PERFORMANCE IMPOSSIBLE
10
DECISION TREE IS ENTERED HERE

APPENDIX D

Questionnaire

Please rate each of the different display types on each of the categories below according to the following scale:

1 - Not useful at all
2 - Much worse than what I am used to
3 - Worse than what I am used to
4 - The same as what I am used to
5 - Better than what I am used to
6 - Much better than what I am used to
7 - Superior, adds a new level of awareness

	Text Only	Static	Moving
Ability to maintain situation awareness:	_____	_____	_____
Overall mental workload:	_____	_____	_____
Ease of use of the display:	_____	_____	_____
Readability of the display:	_____	_____	_____
Depiction of the missed approach:	_____	_____	_____
Overall rating:	_____	_____	_____

Please comment below on any features of the displays that you thought were particularly useful or that were distracting or not useful: